

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

R.J. deBoer¹, R.E. Azuma^{1,2}, E. Uberseder¹,
J. Görres¹, G. Imbriani^{1,3}, P.J. LeBlanc¹, and M. Wiescher¹

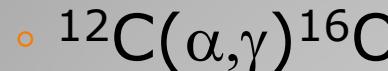
¹University of Notre Dame

²University of Toronto

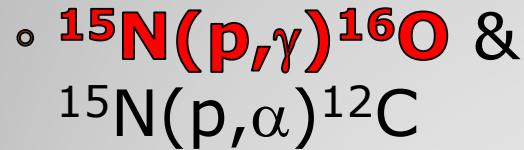
³Università degli Studi di Napoli “Federico II” and INFN



• Nuclear Astrophysics

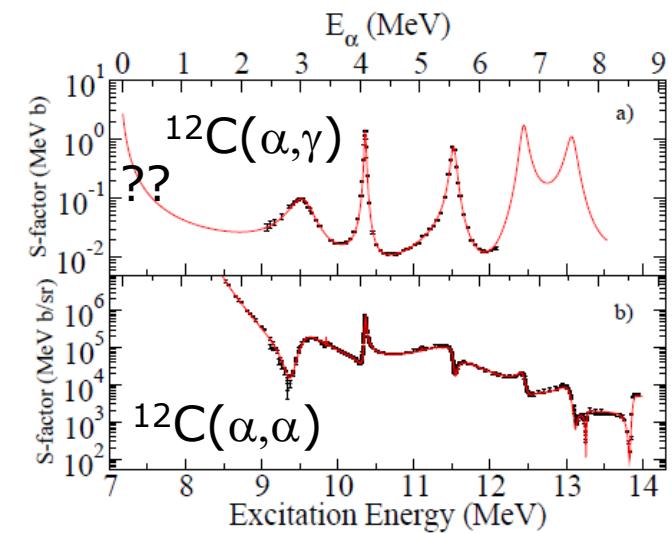


- Main energy producing reaction during helium burning
- “Holy Grail” of nuclear astrophysics

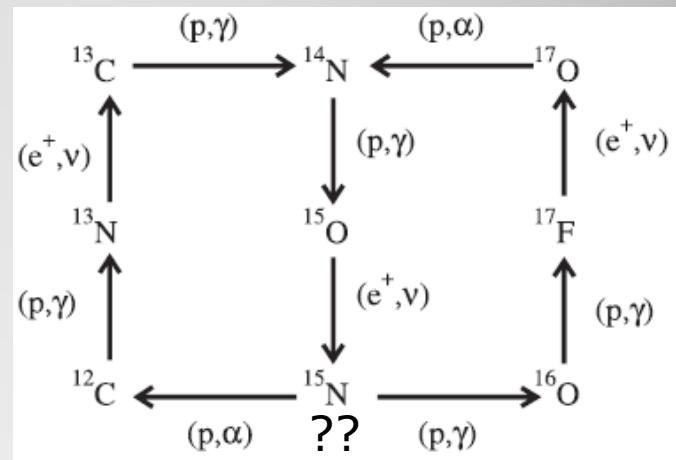


- Branch point for the CNO bi-cycle during stellar hydrogen burning

Motivation



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

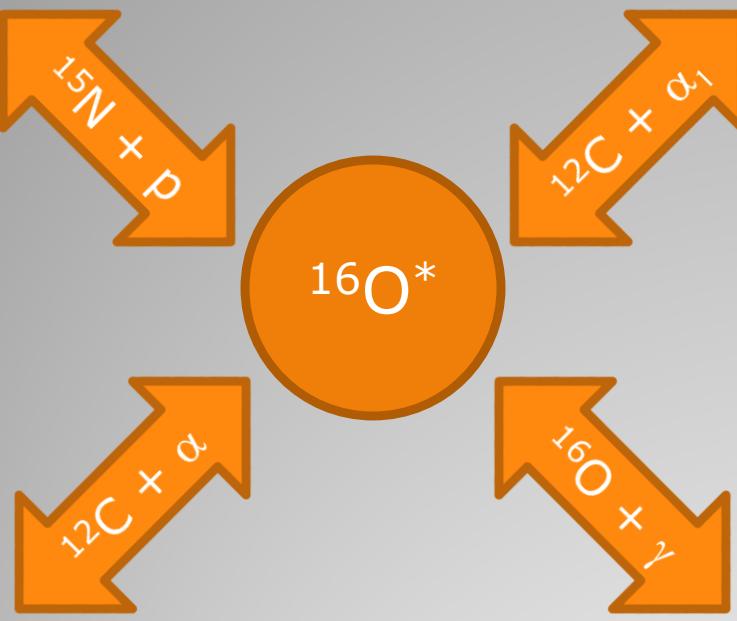


LeBlanc *et al.* (2010)

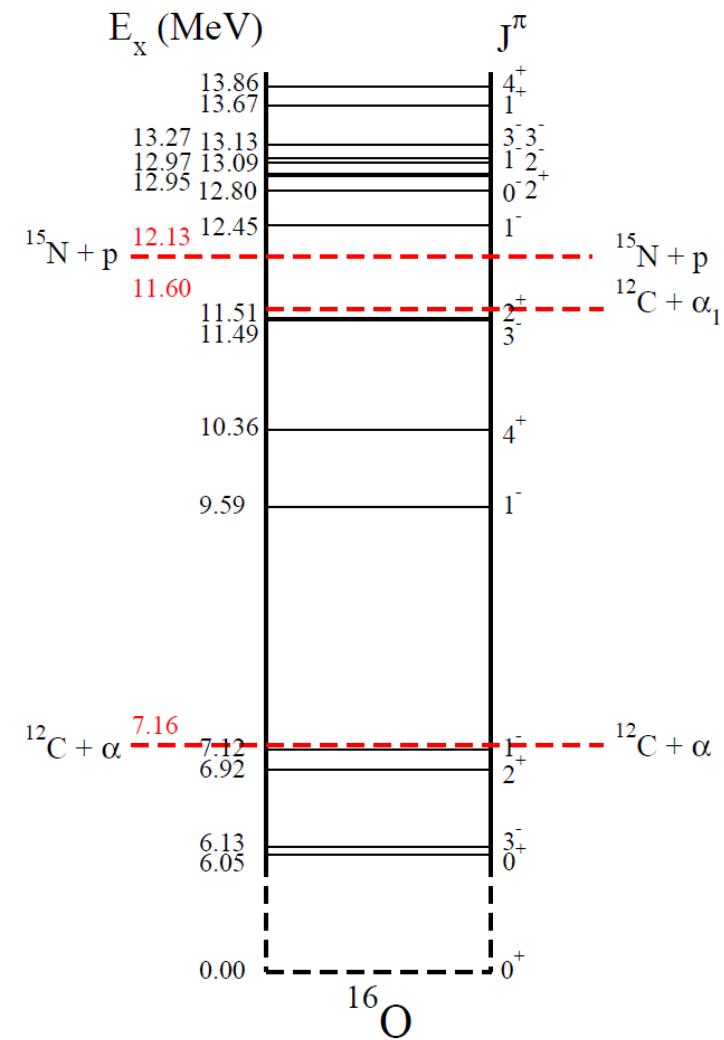
- AZURE updates
 - Rewritten in C++ (E. Uberseder)
 - Multiple entrance channels
 - Multi-core processing using MINUIT2
 - New GUI interface (QT)
 - Dynamic memory allocation = more data
 - Alternative R-matrix parameterization of (Brune 2002), on-resonance parameters only
 - NOT yet available for public 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)**





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



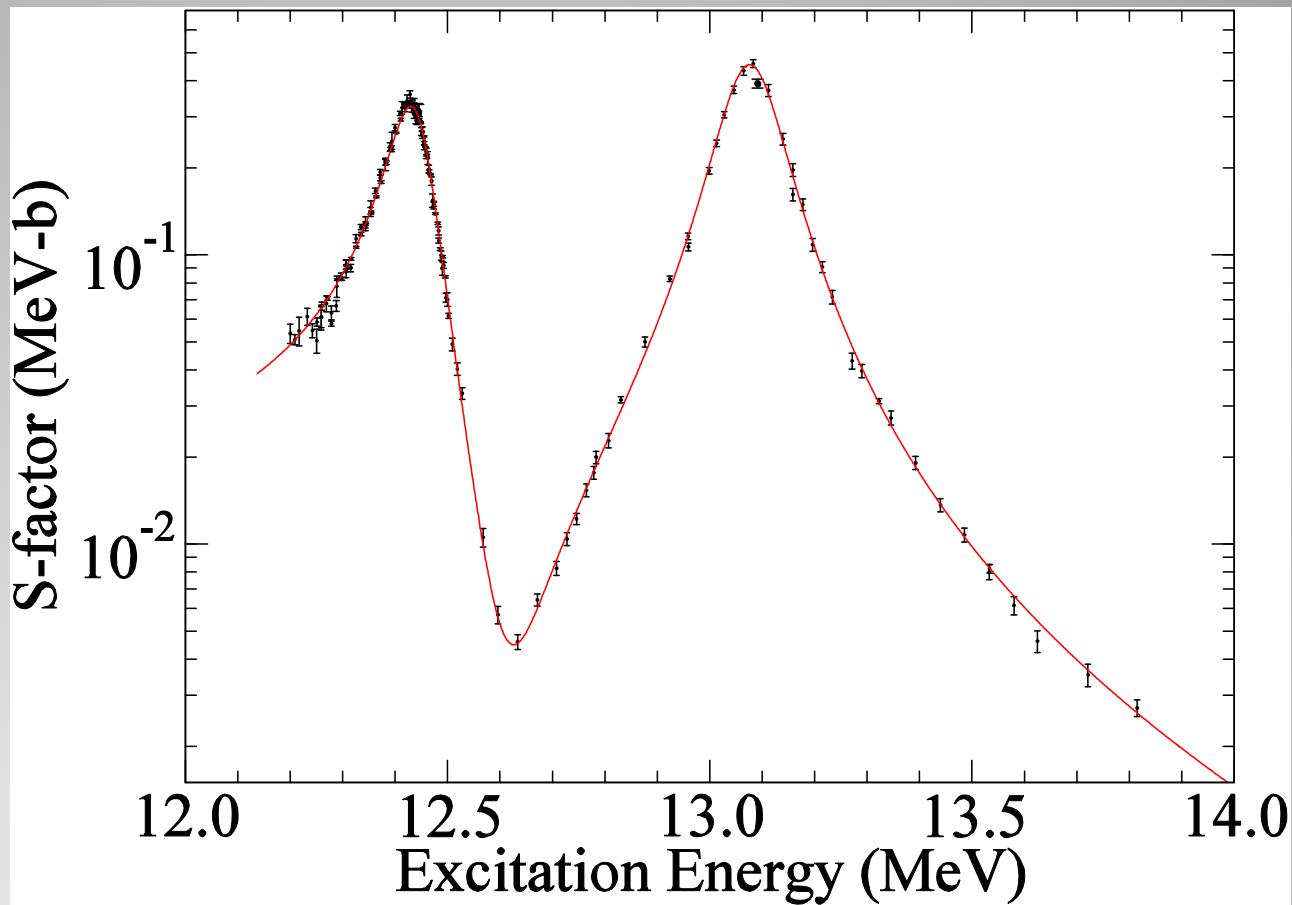
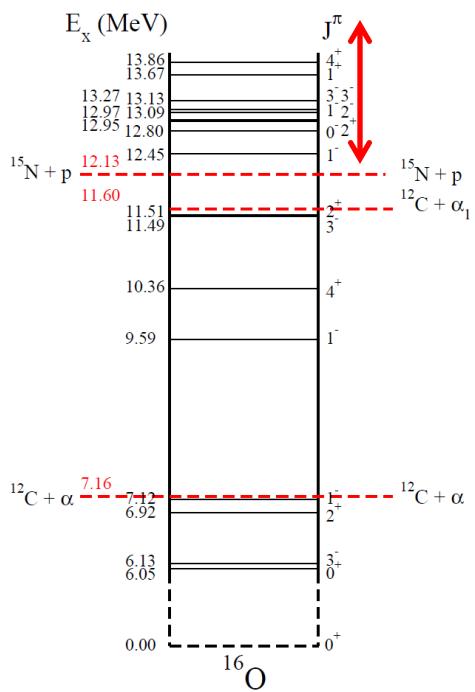
Same energies and partial widths

Structure of ^{16}O

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

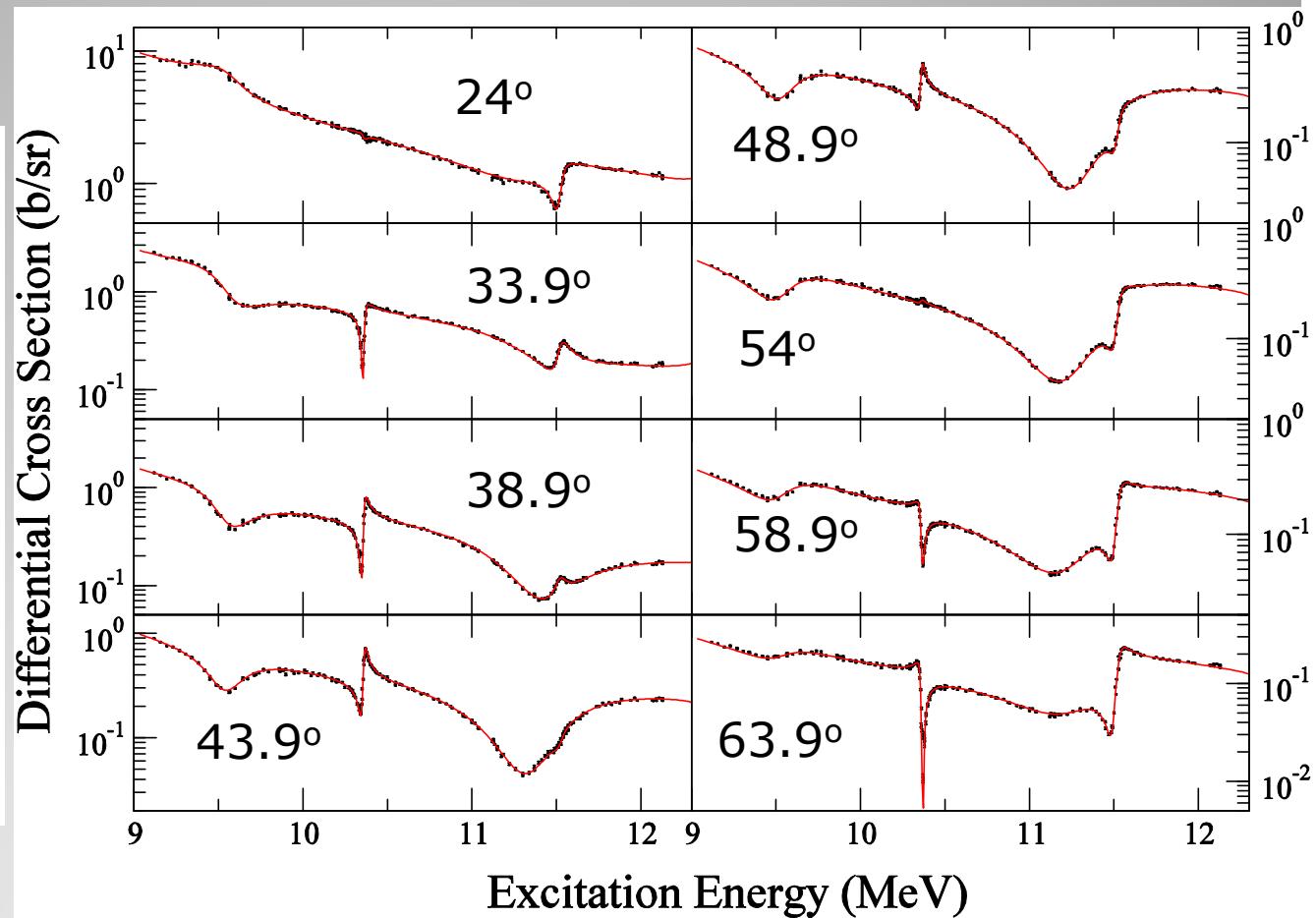
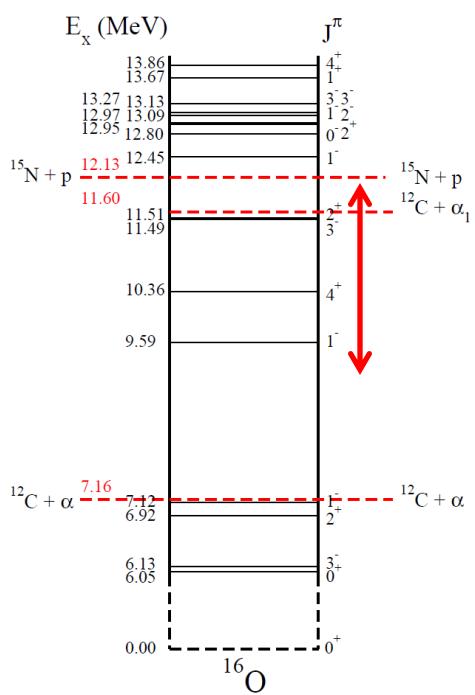
| Ref. | Reaction(s) |
|-------------------------------------|---|
| Schardt et al. [15] (1952) | (p, α_0) |
| Hagedorn [16] (1957) | (p, p) |
| Hagedorn and Marion [17] (1957) | (p, α_0) |
| Bashkin et al. [18] (1959) | (p, p), (p, α_0), (p, α_1) |
| Hebbard [7] (1960) | (p, γ_0) |
| Larson and Spear [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



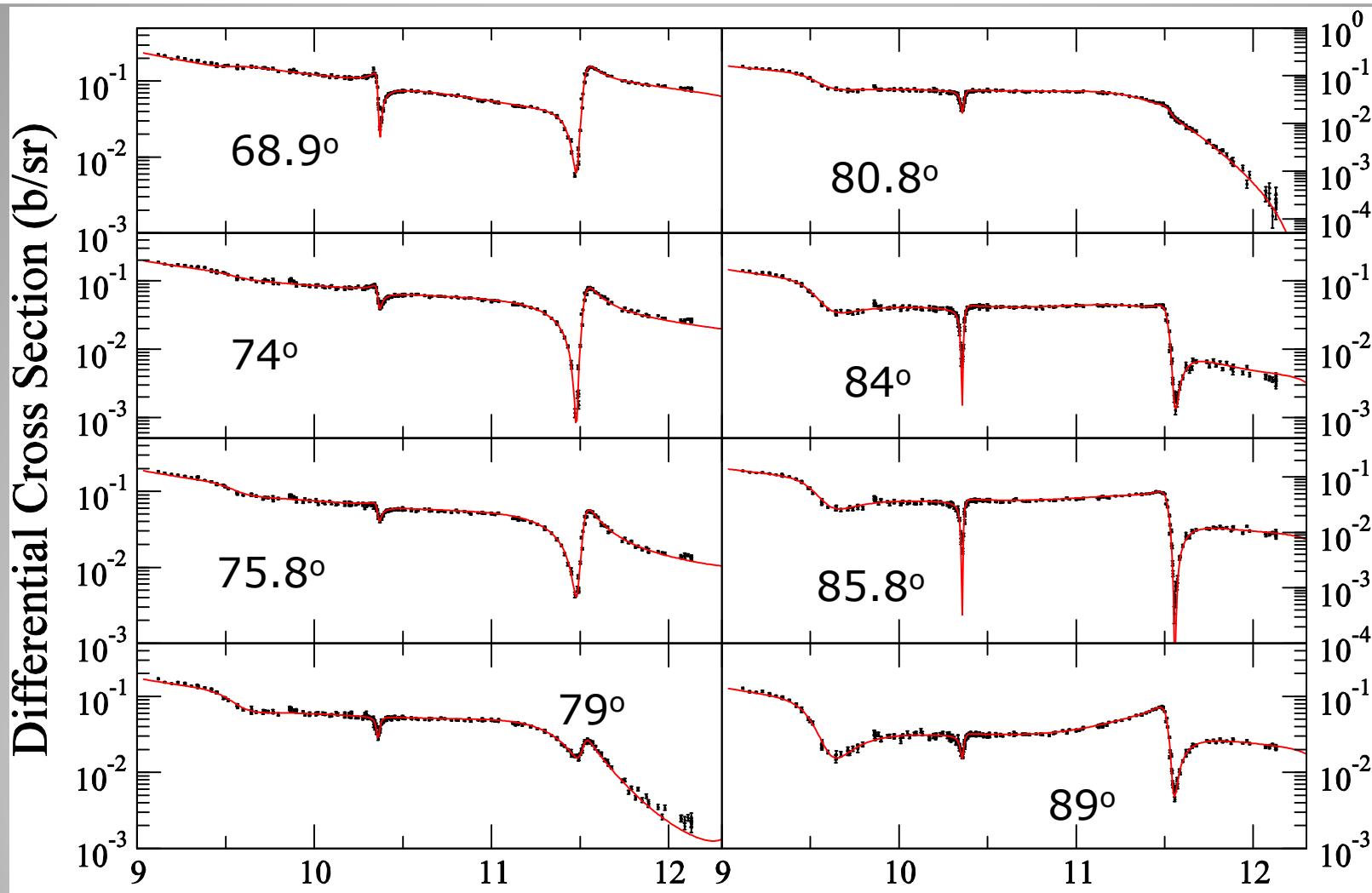
$^{15}\text{N}(\text{p}, \gamma_0)$

LeBlanc *et al.* (2010) and Caciolli
et al. (2011)



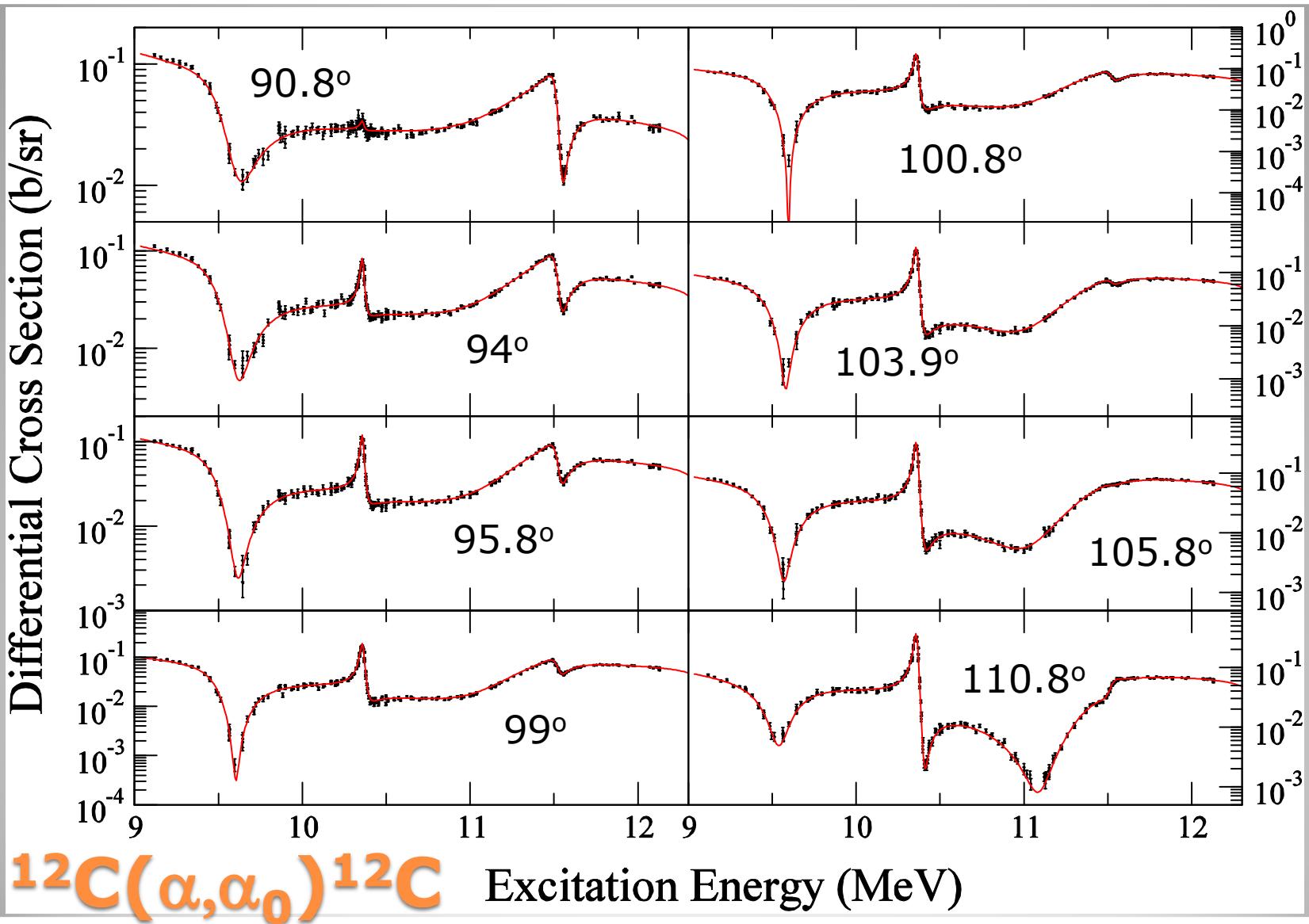
$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$

Tischhauser *et al.* (2009)

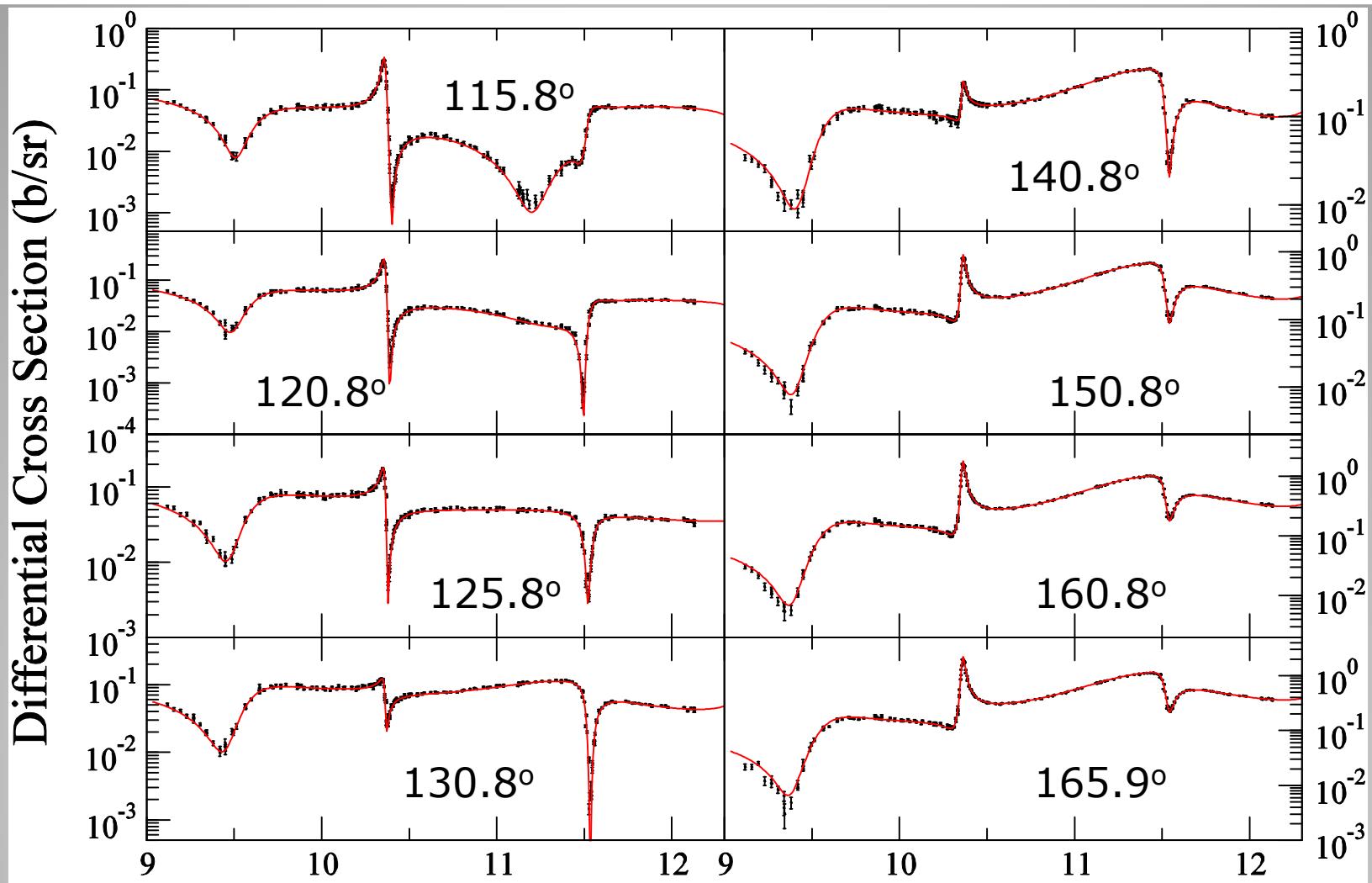


$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$ Excitation Energy (MeV)

Tischhauser et al. (2009)

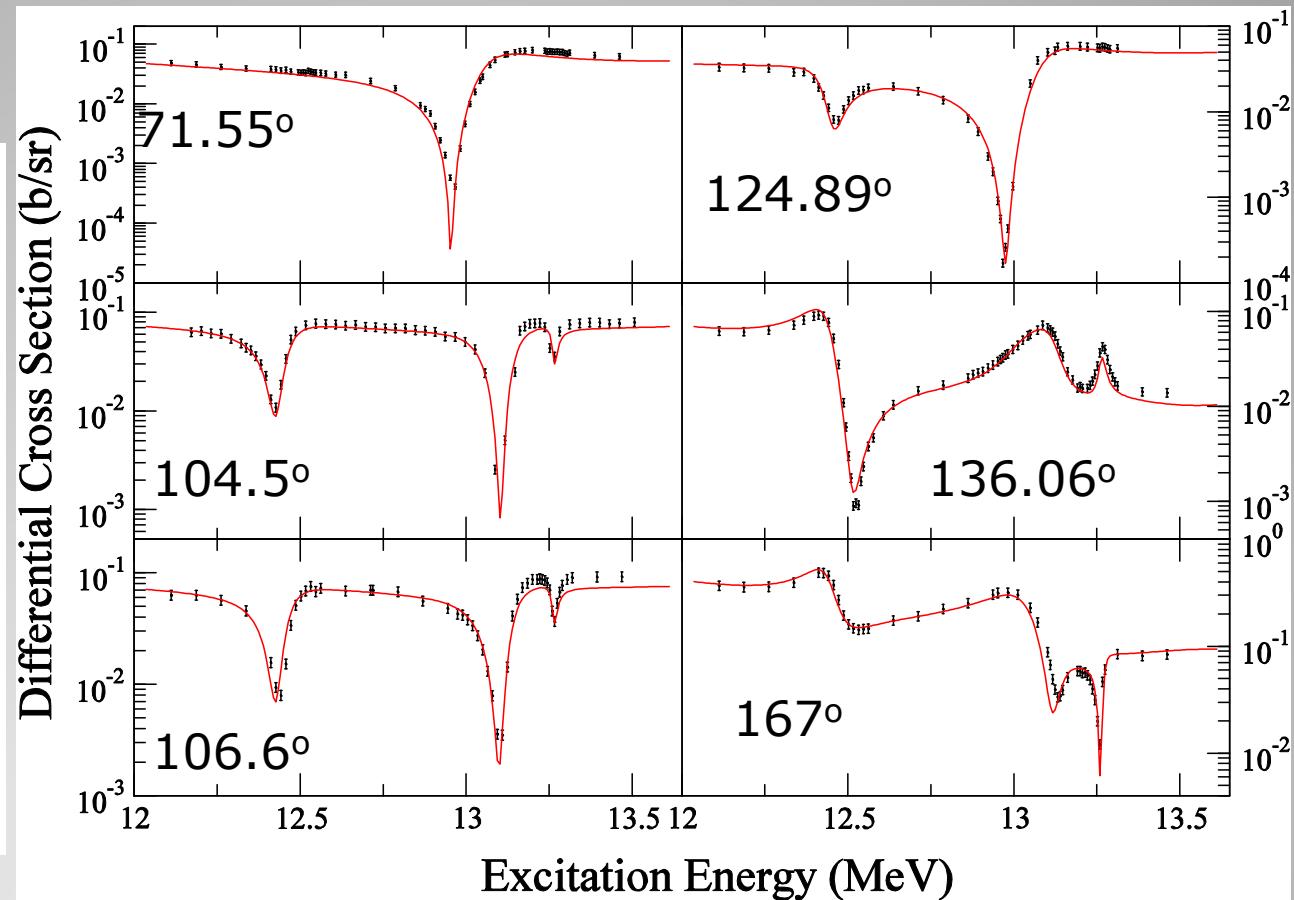
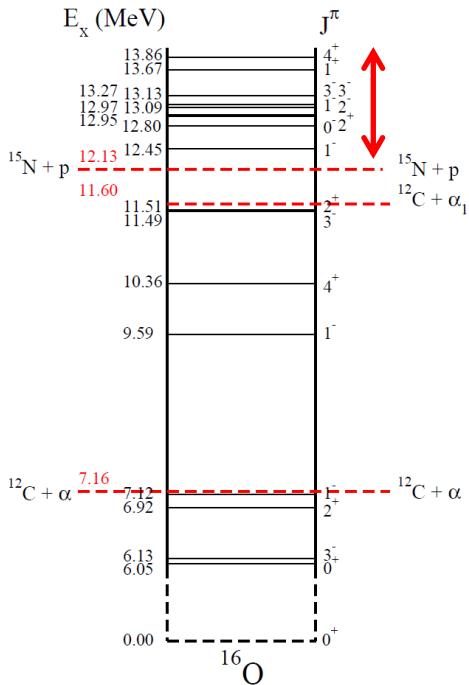


Tischhauser *et al.* (2009)

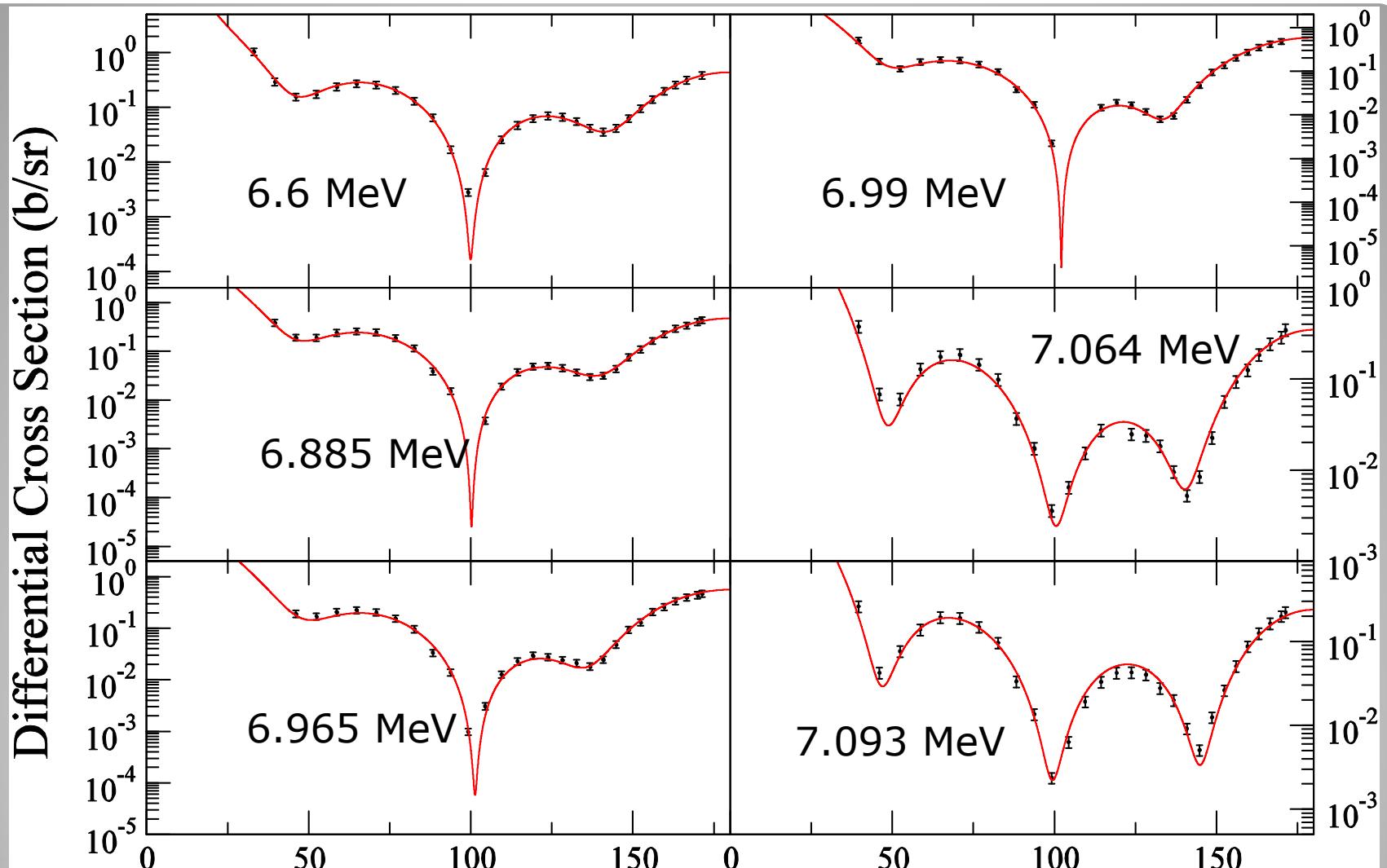


$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$ Excitation Energy (MeV)

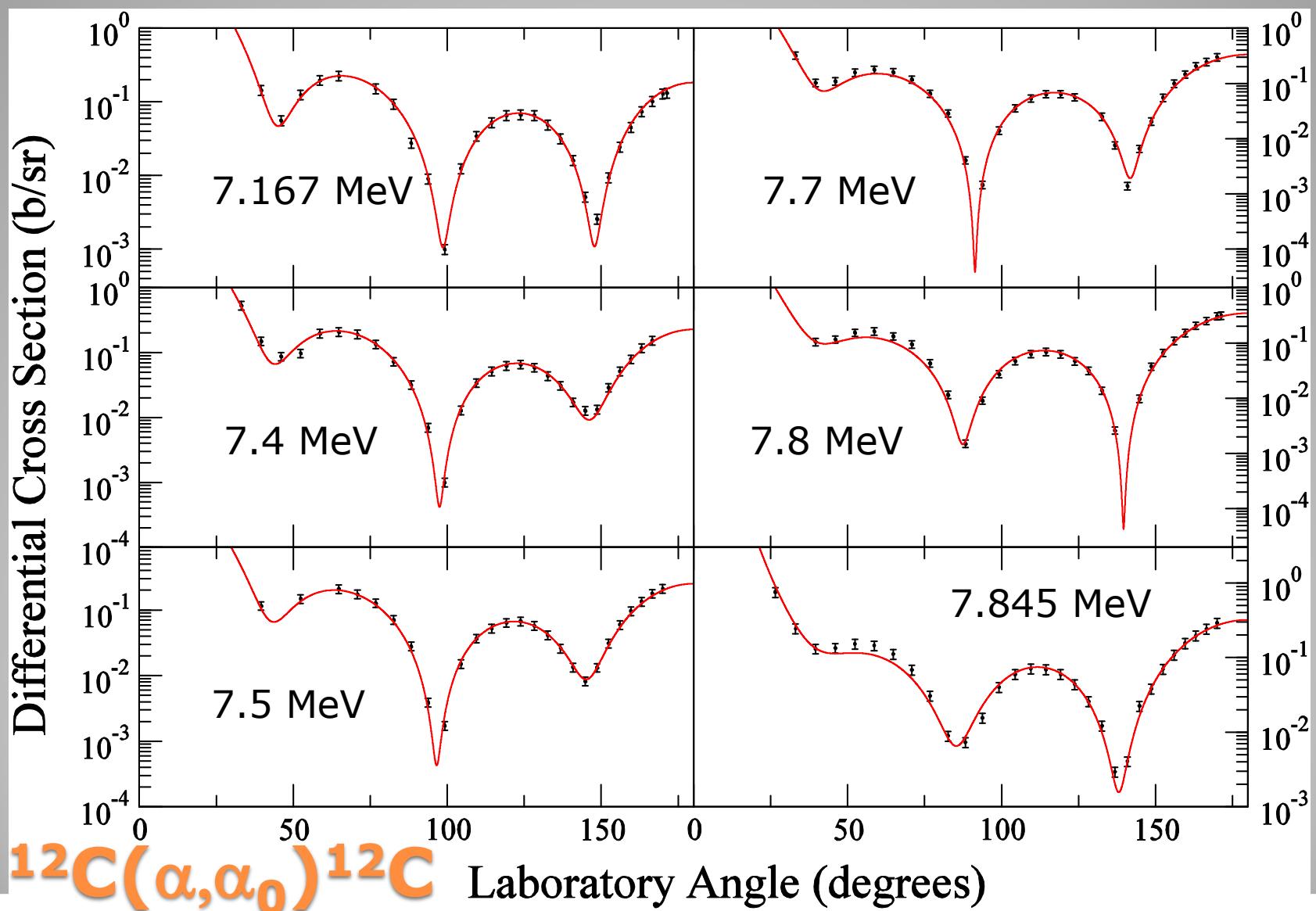
Tischhauser *et al.* (2009)



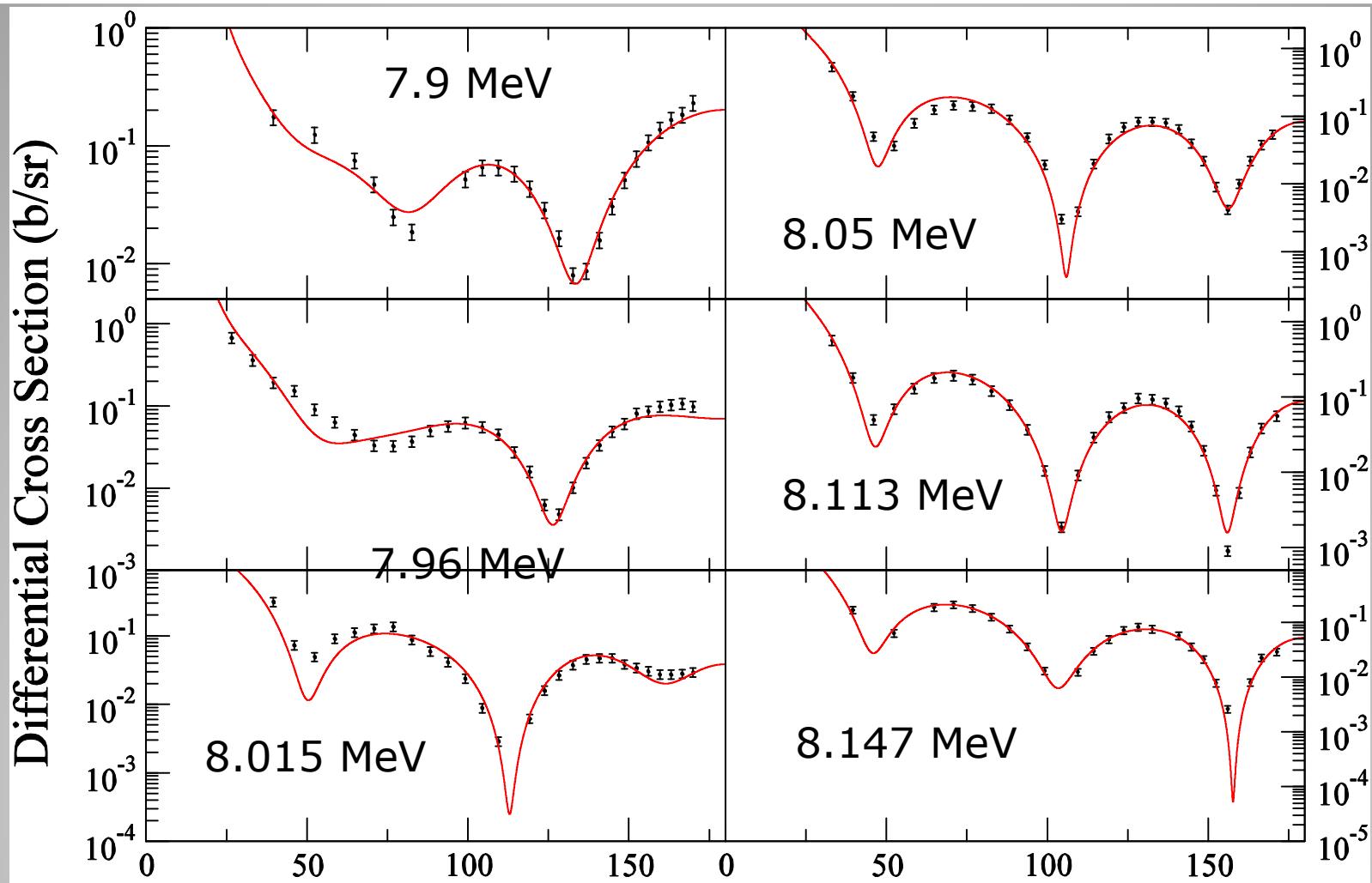
$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$
Morris et al. (1968)



$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$ Laboratory Angle (degrees)
Morris et al. (1968)

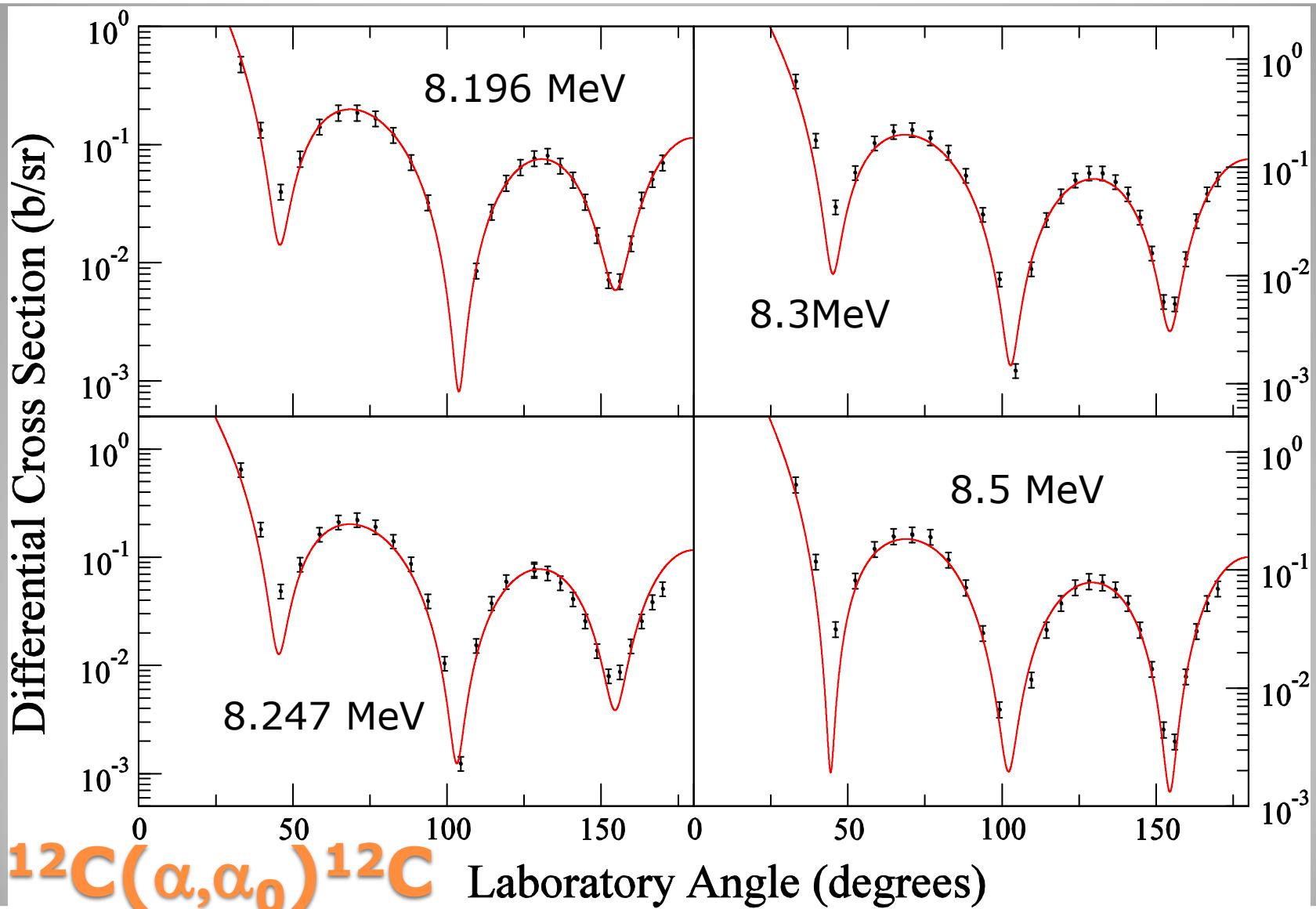


$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$ Morris et al. (1968)

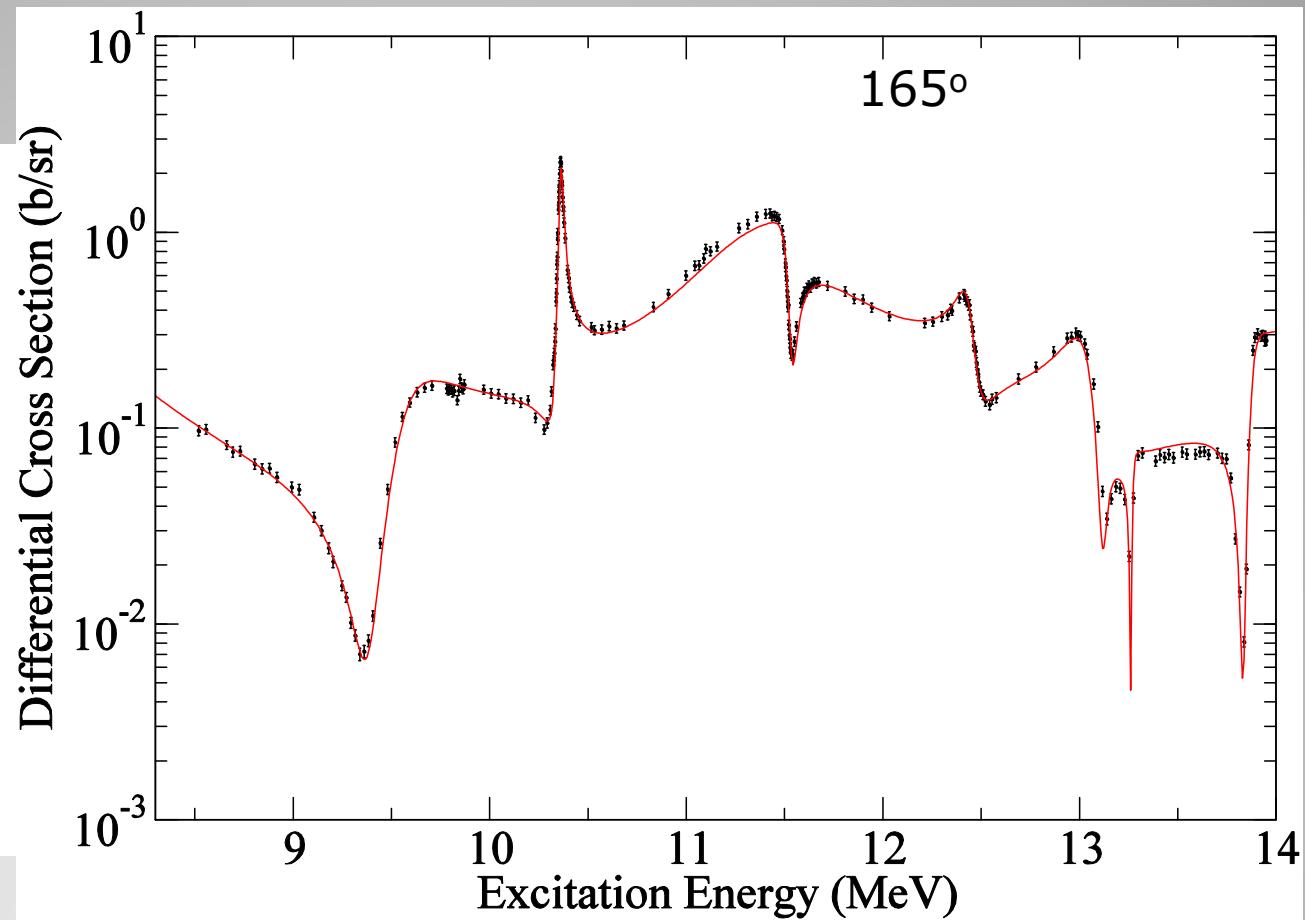
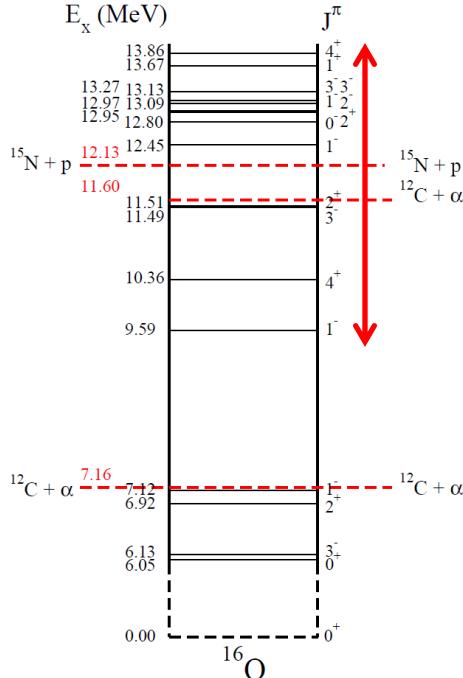


$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$ Laboratory Angle (degrees)

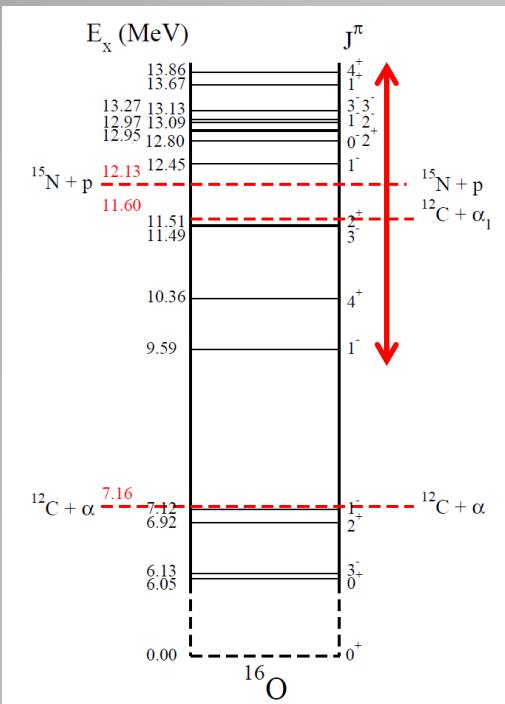
Morris et al. (1968)



Morris et al. (1968)

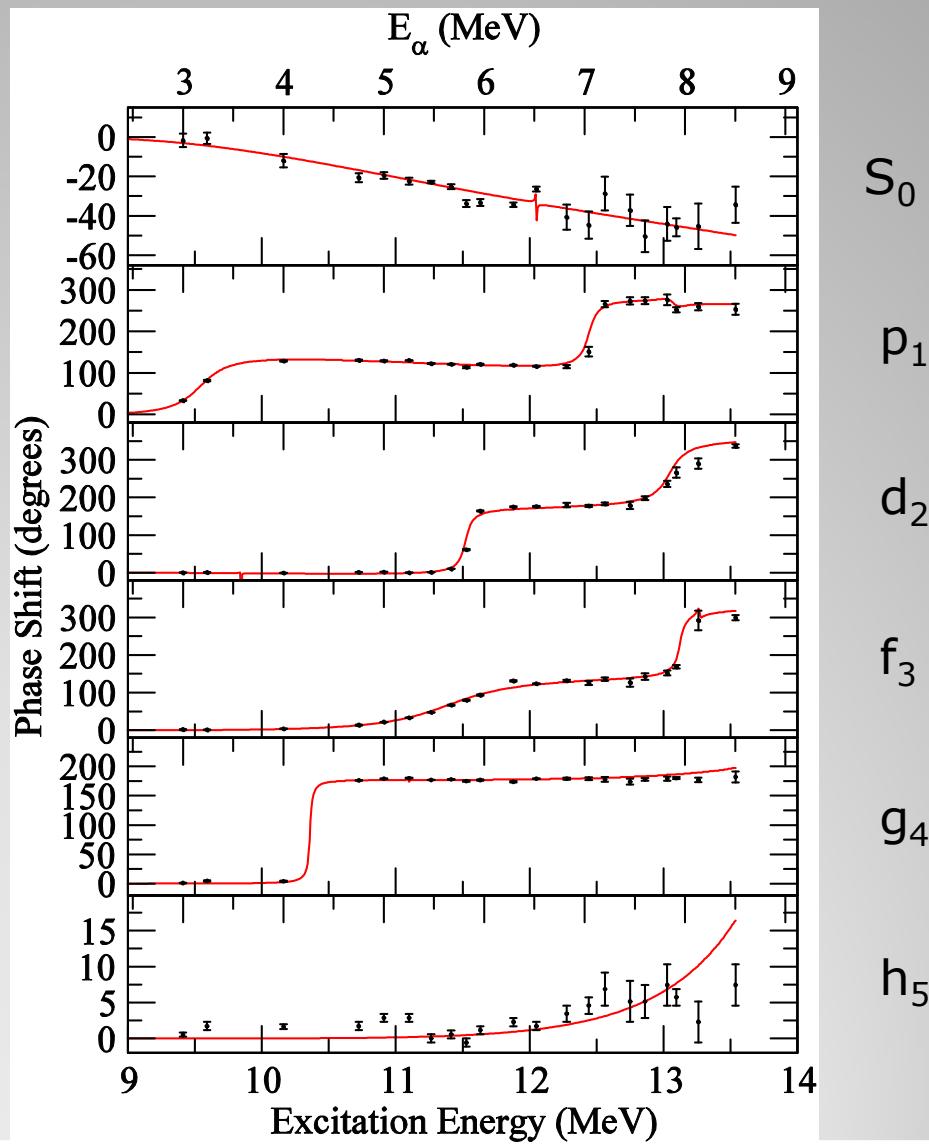


$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$
Feng et al. (1994)

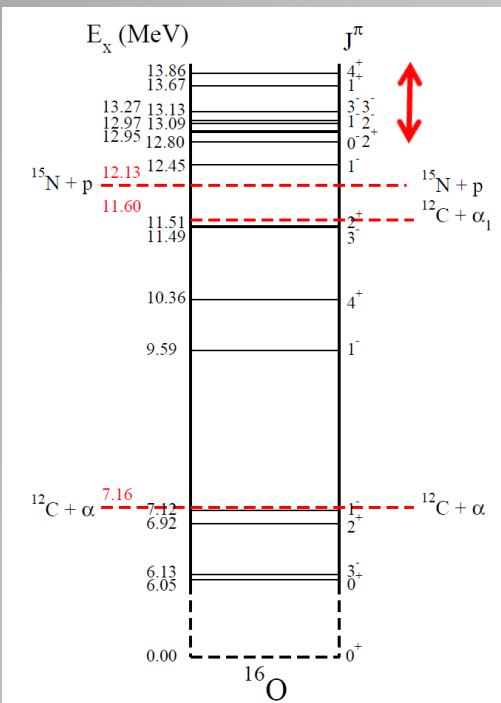


$^{12}\text{C}(\alpha, \alpha_0)^{12}\text{C}$

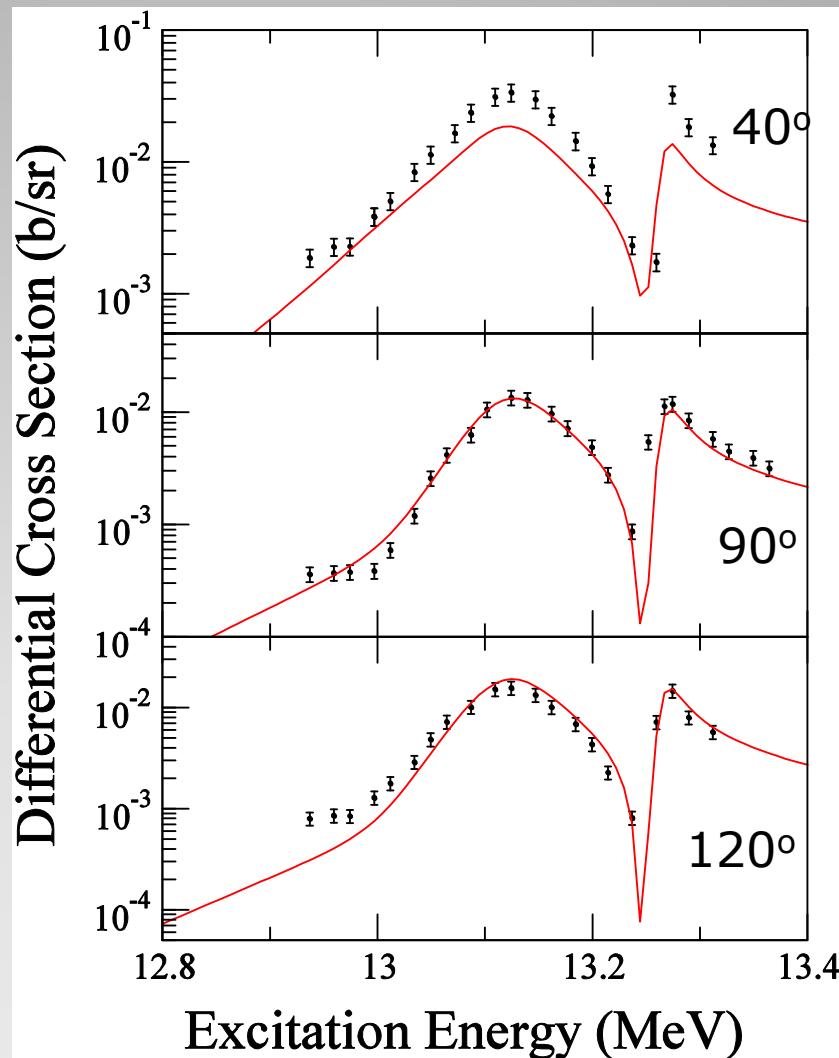
D'Agostino Bruno *et al.* (1975)

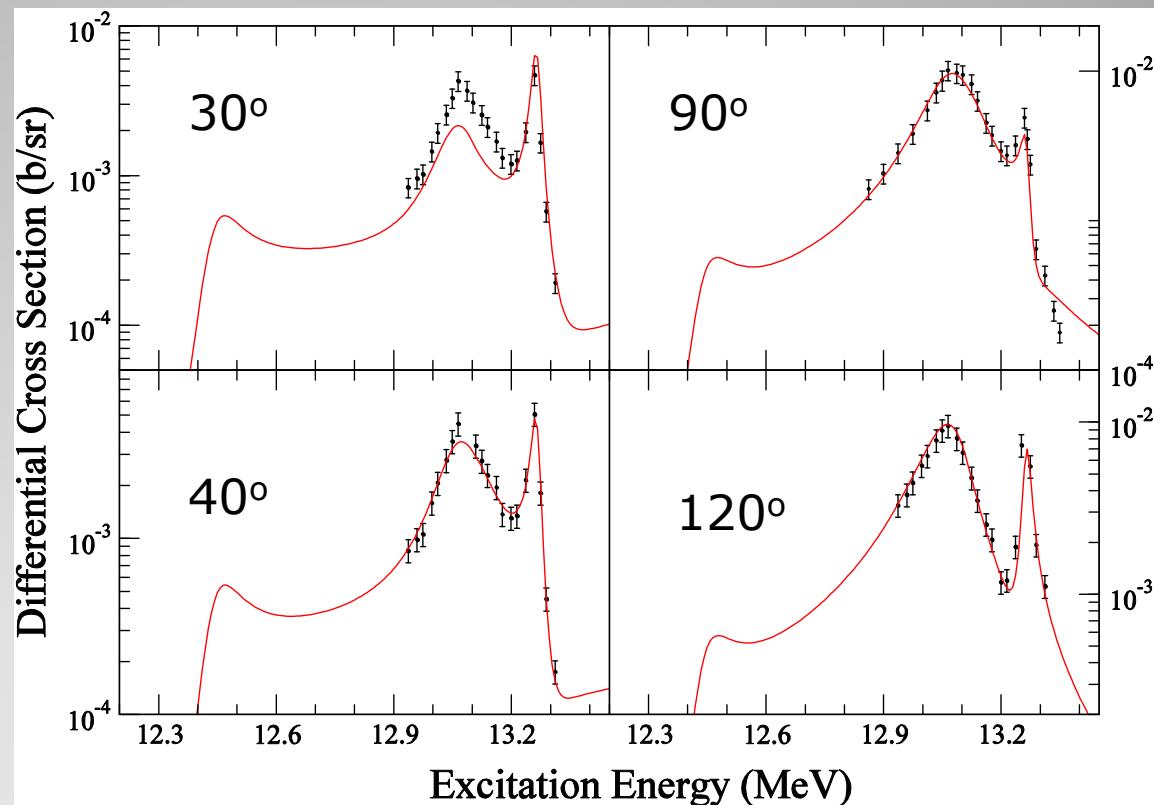
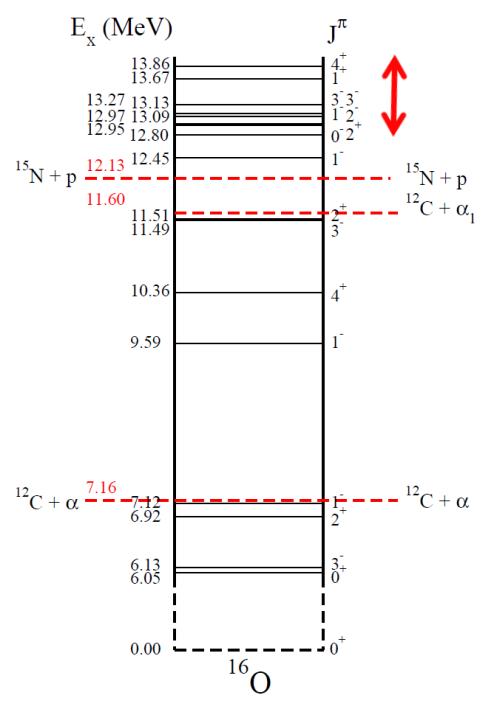


S_0
 p_1
 d_2
 f_3
 g_4
 h_5

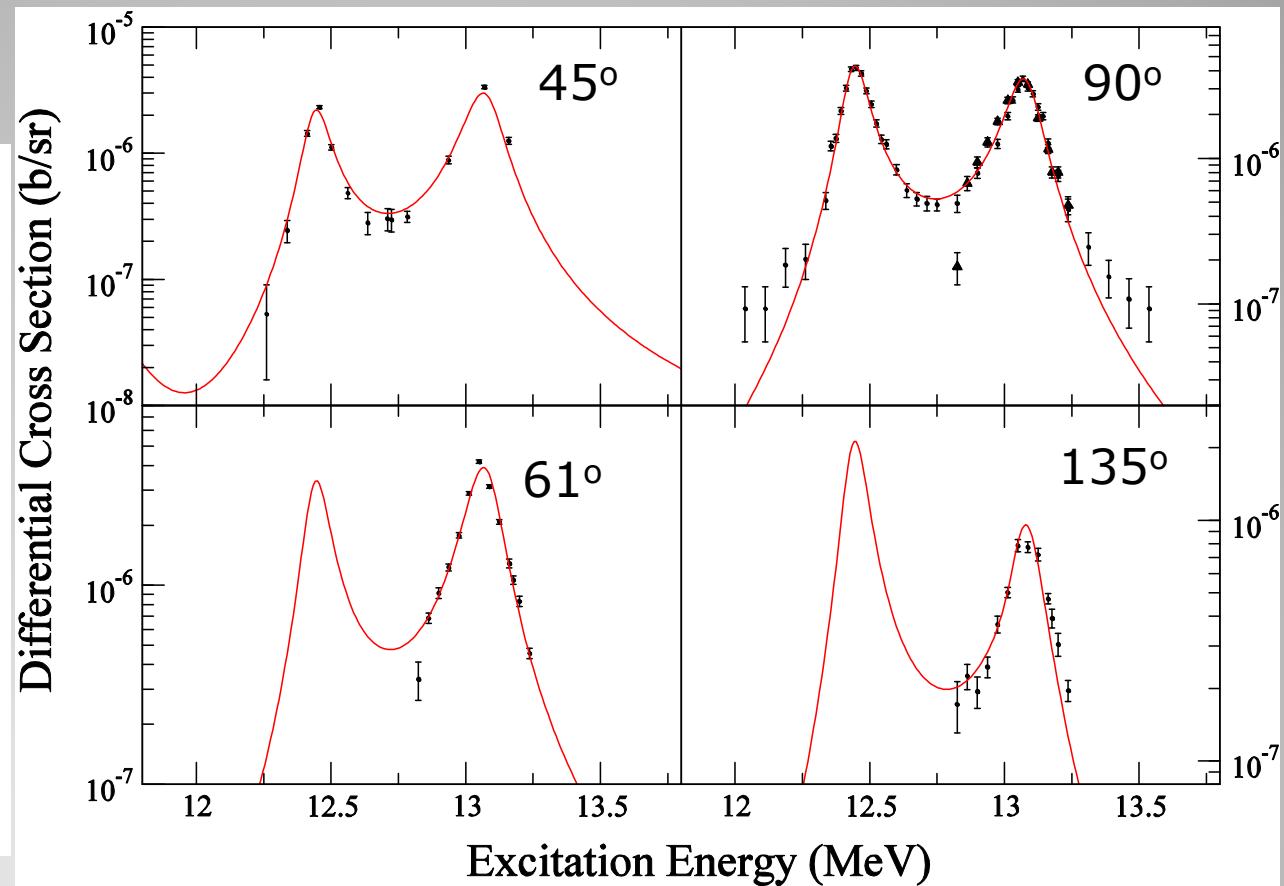
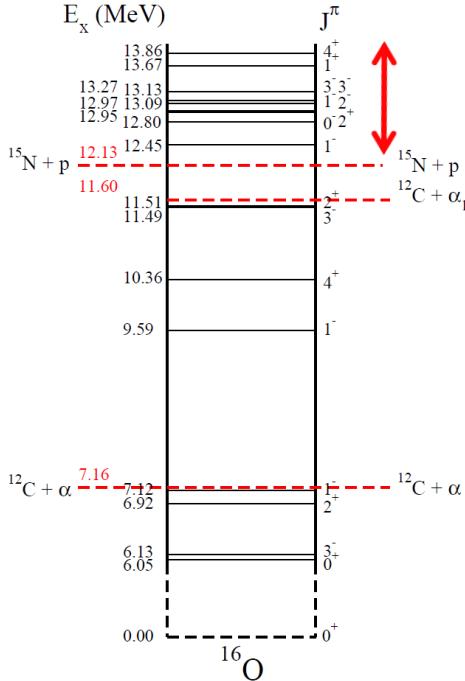


$^{12}\text{C}(\alpha, \alpha_1)^{12}\text{C}$
Mitchell and Ophel (1965)



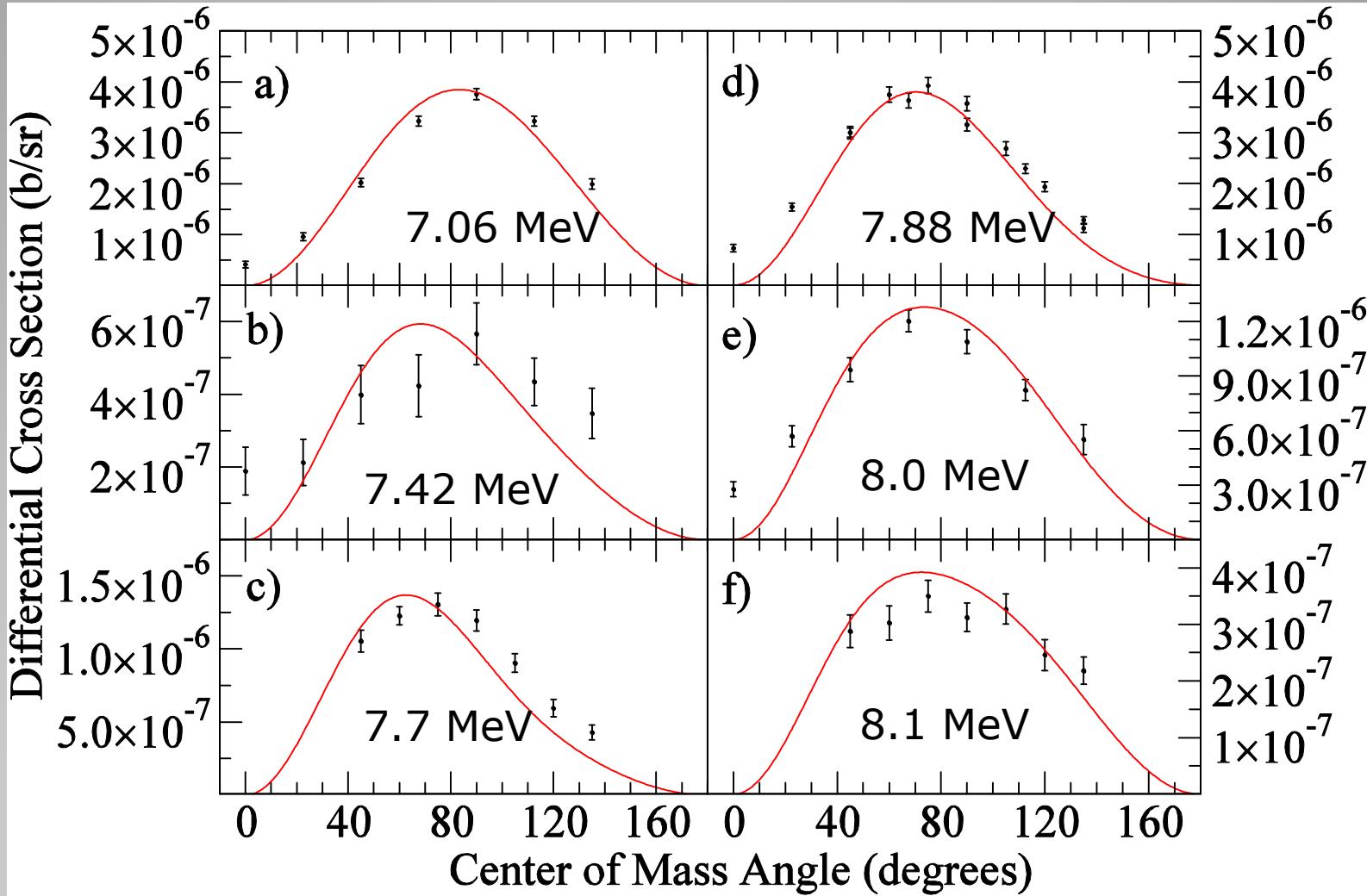


$^{12}\text{C}(\alpha, \text{p})^{15}\text{N}$
Mitchell and Ophel (1965)

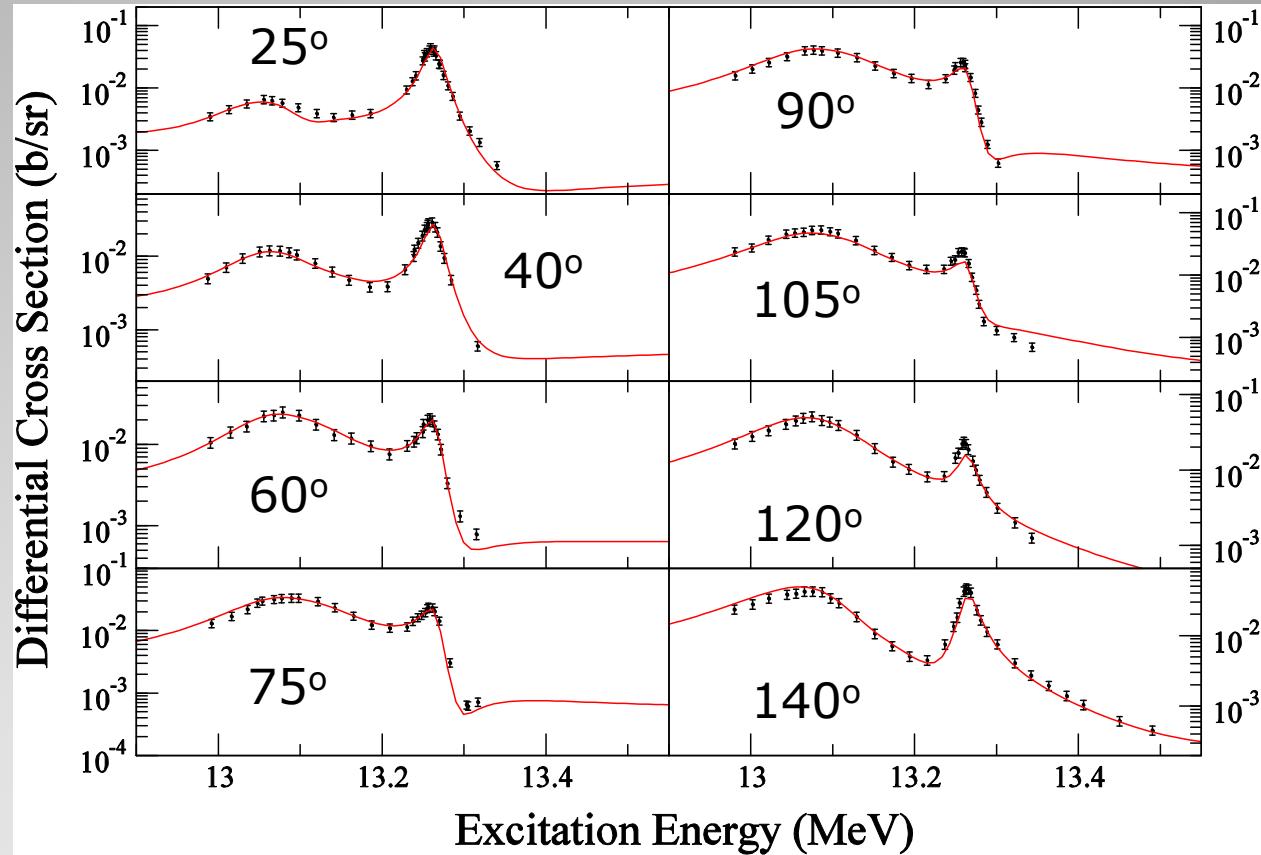
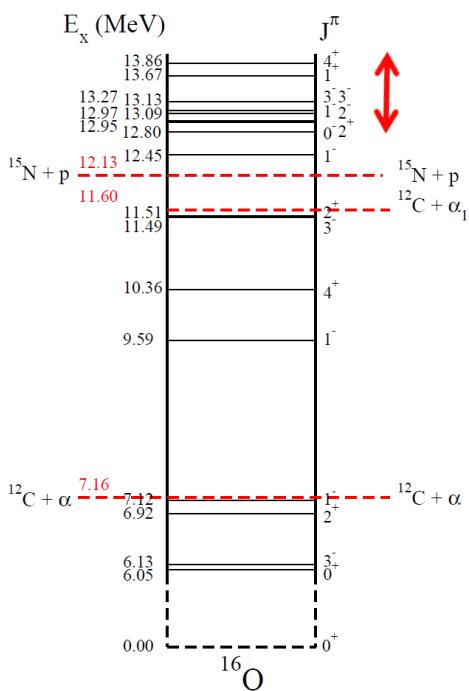


$^{12}\text{C}(\alpha, \gamma_0)^{16}\text{O}$

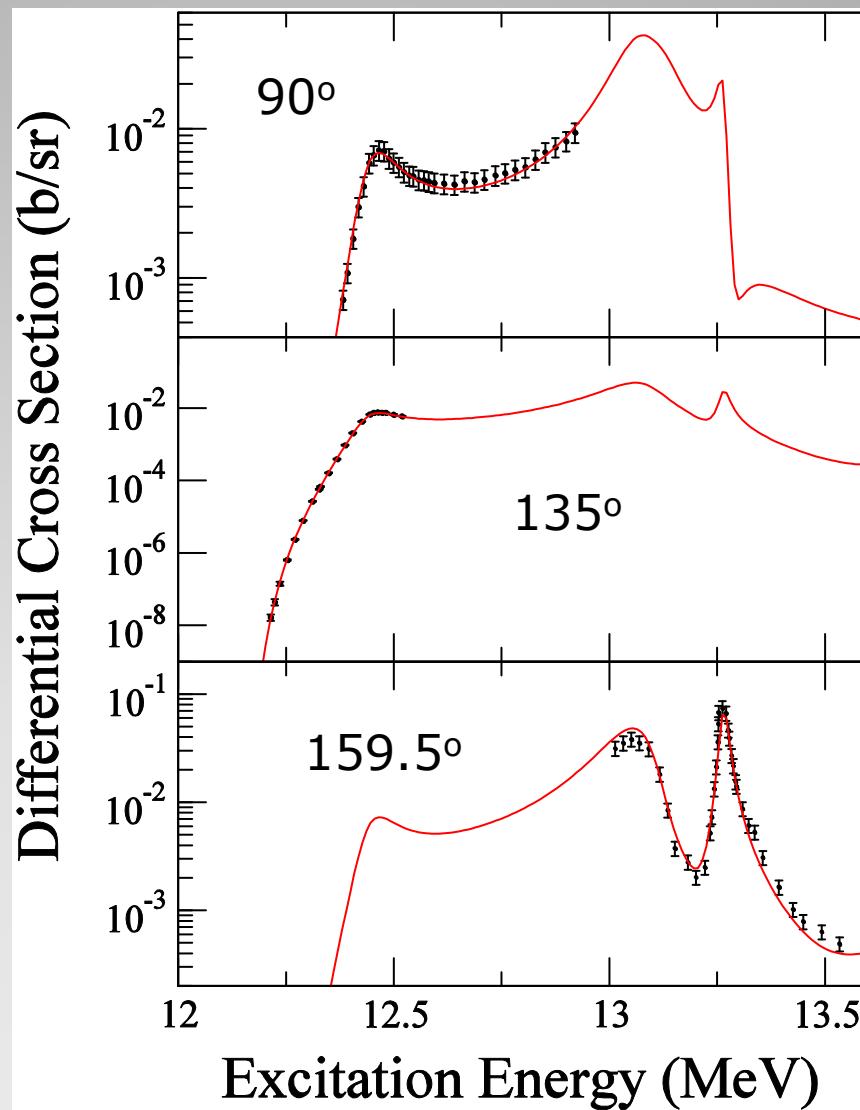
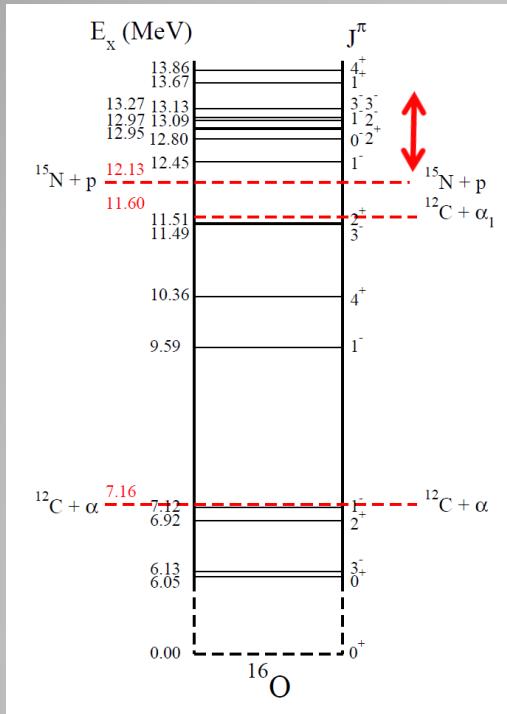
Ophel *et al.* (1976), Larson and Spear (1964), and Kernel *et al.* (1971)



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

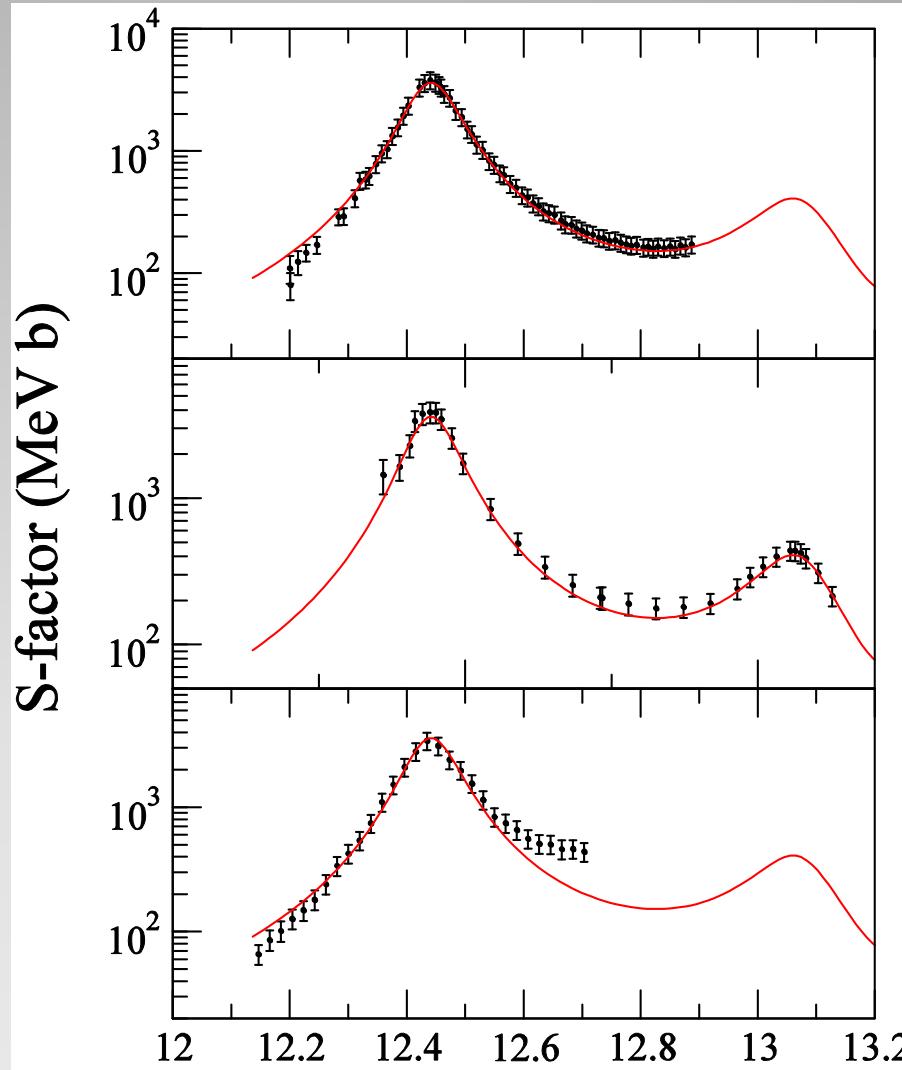


$^{15}\text{N}(\text{p},\alpha_0)^{12}\text{C}$
Hagedorn and Marion (1957)



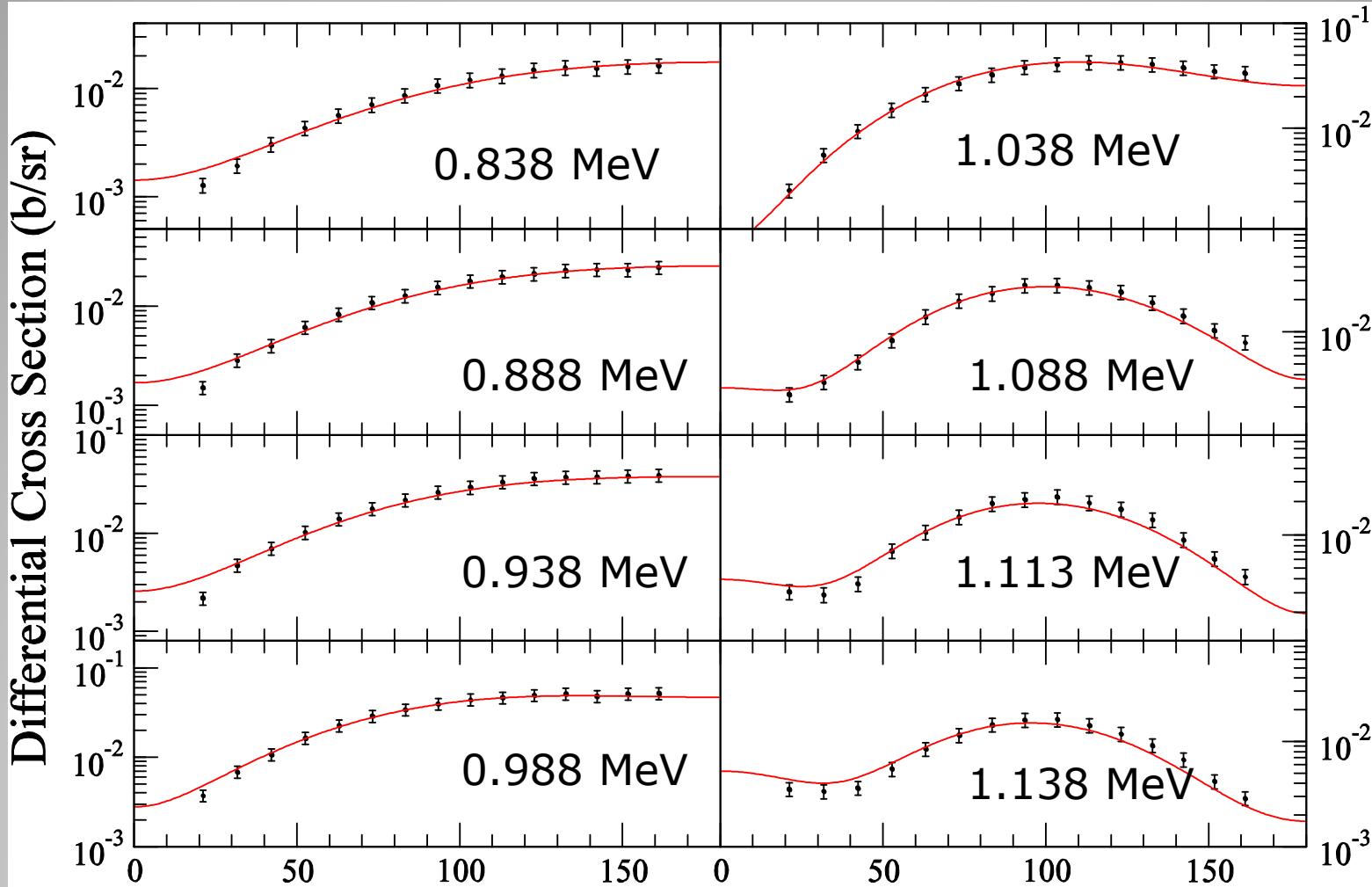
$^{15}\text{N}(\text{p},\alpha_0)^{12}\text{C}$

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

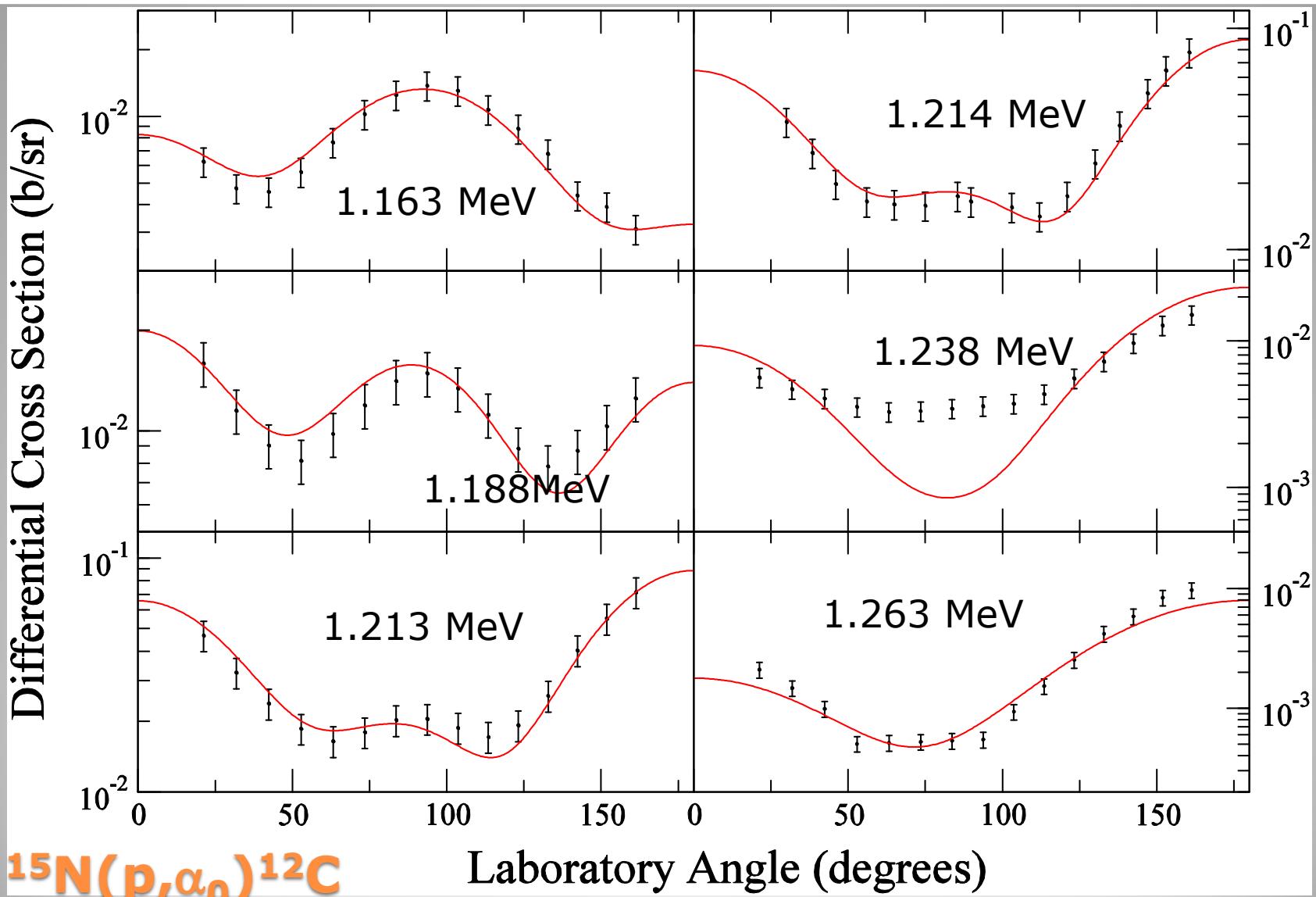


$^{15}\text{N}(\text{p},\alpha_0)^{12}\text{C}$

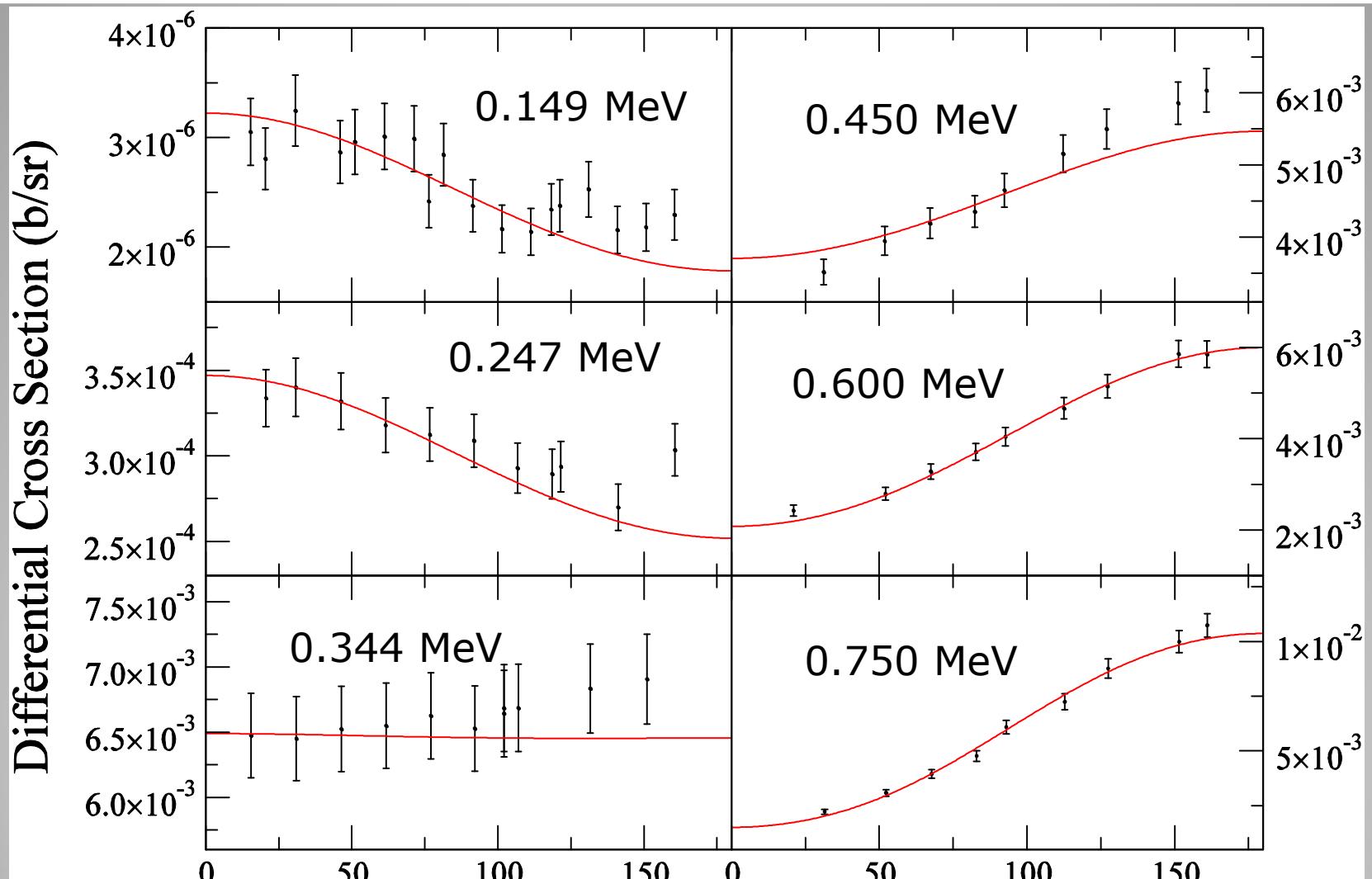
Redder et al. (1982), Brochard et al. (1973),
and La Cognata et al. (2009)



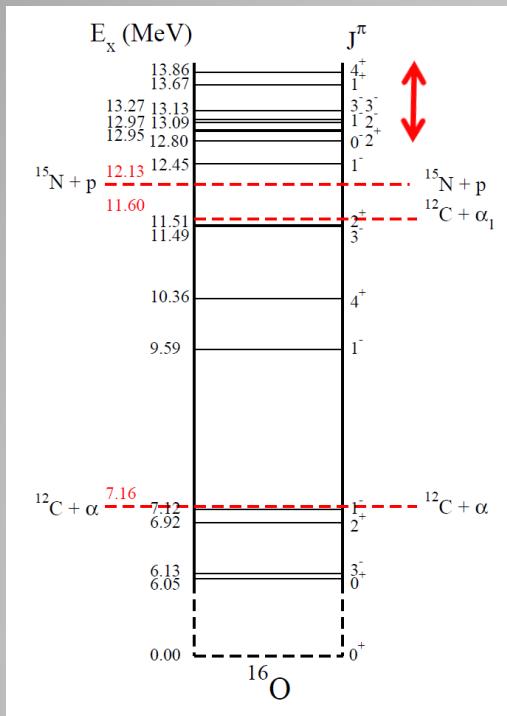
$^{15}\text{N}(\text{p}, \alpha_0)^{12}\text{C}$ Bray et al. (1977)



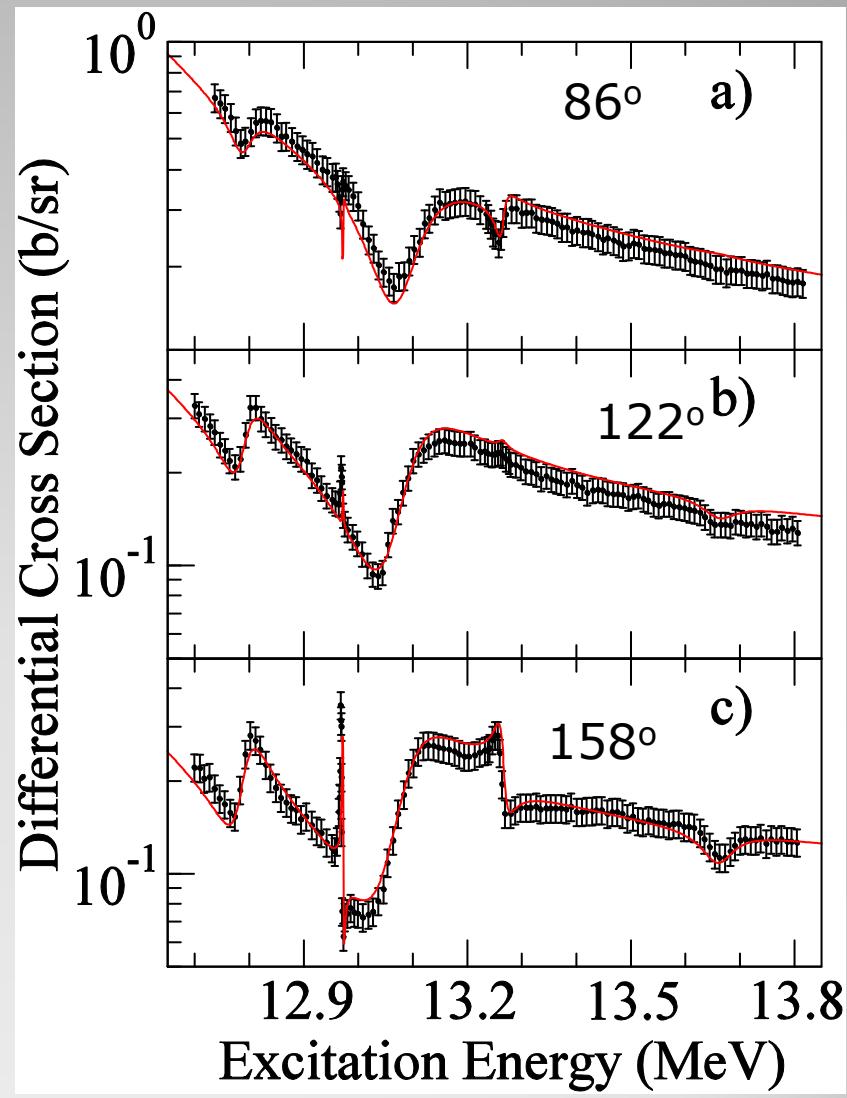
$^{15}\text{N}(\text{p},\alpha_0)^{12}\text{C}$ Bray *et al.* (1977) and Bashkin *et al.* (1959)



$^{15}\text{N}(\text{p}, \alpha_0)^{12}\text{C}$ Laboratory Angle (degrees)
Redder *et al.* (1982)

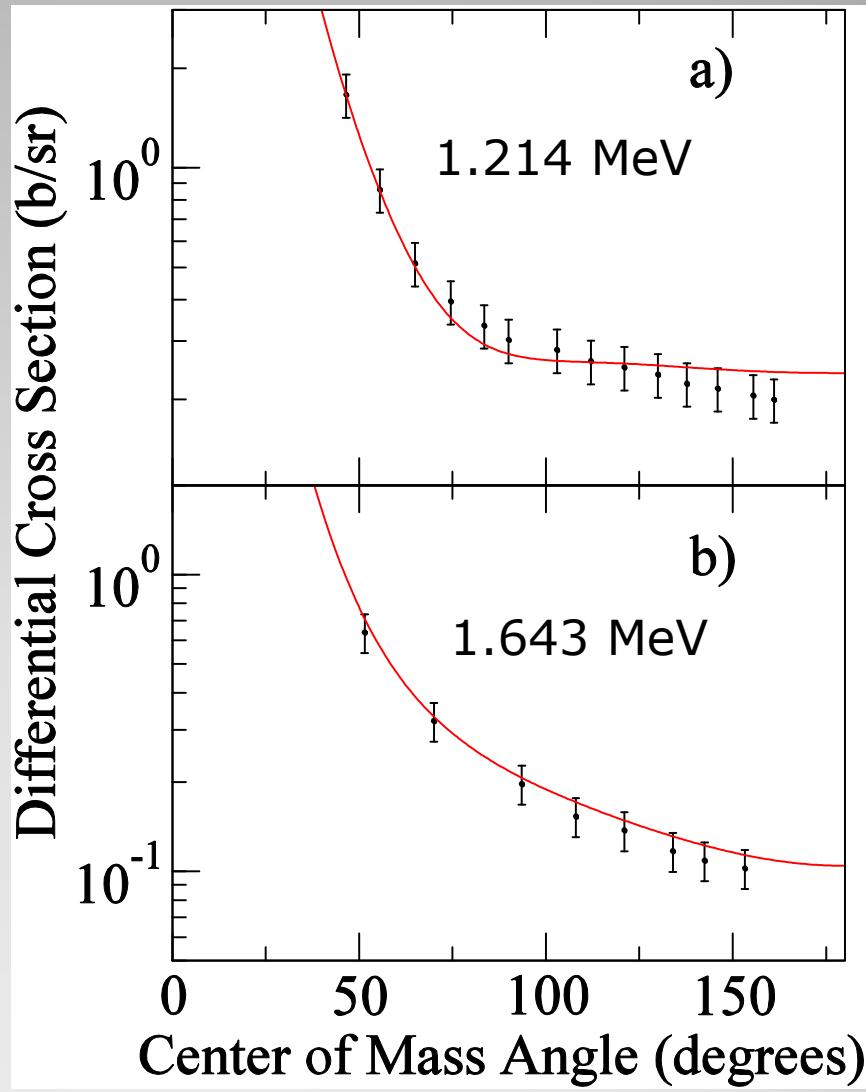


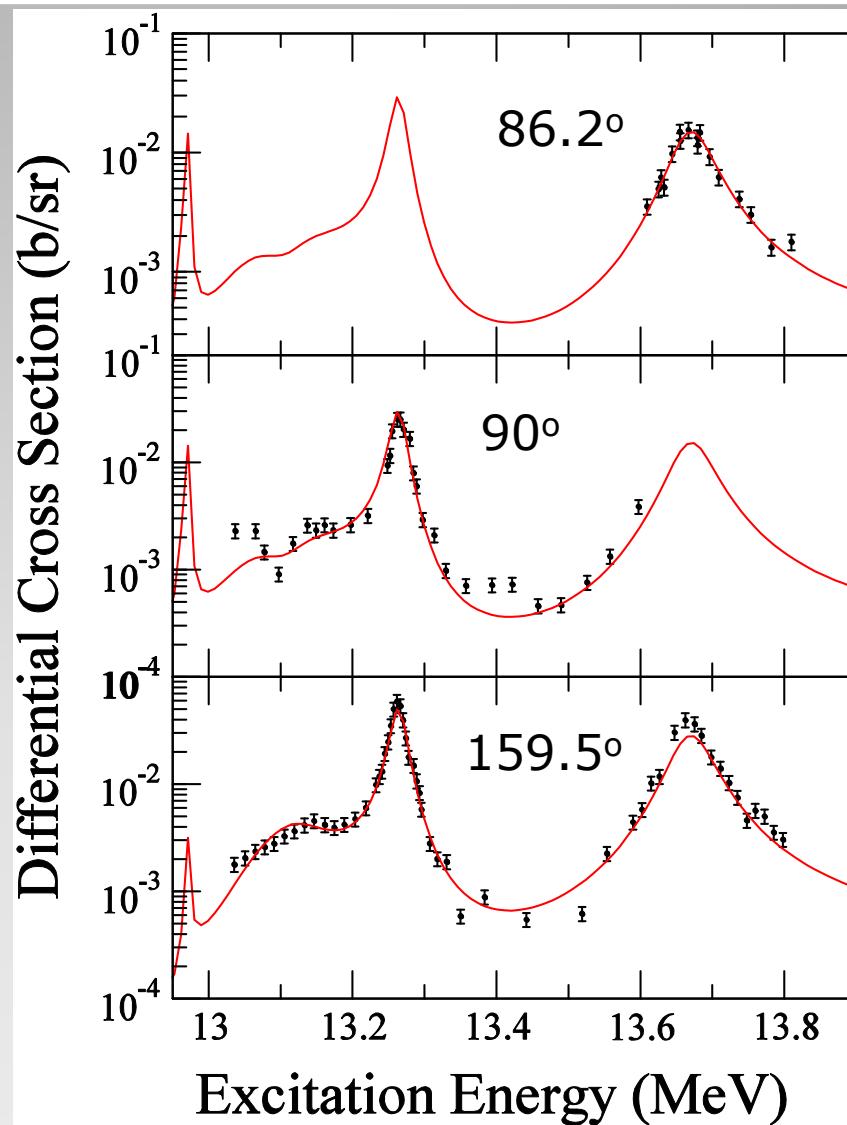
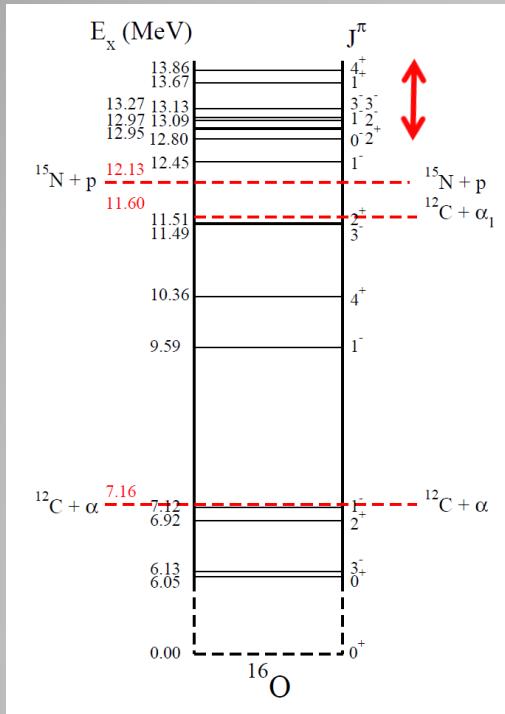
$^{15}\text{N}(\text{p},\text{p})^{15}\text{N}$
Hagedorn (1957)





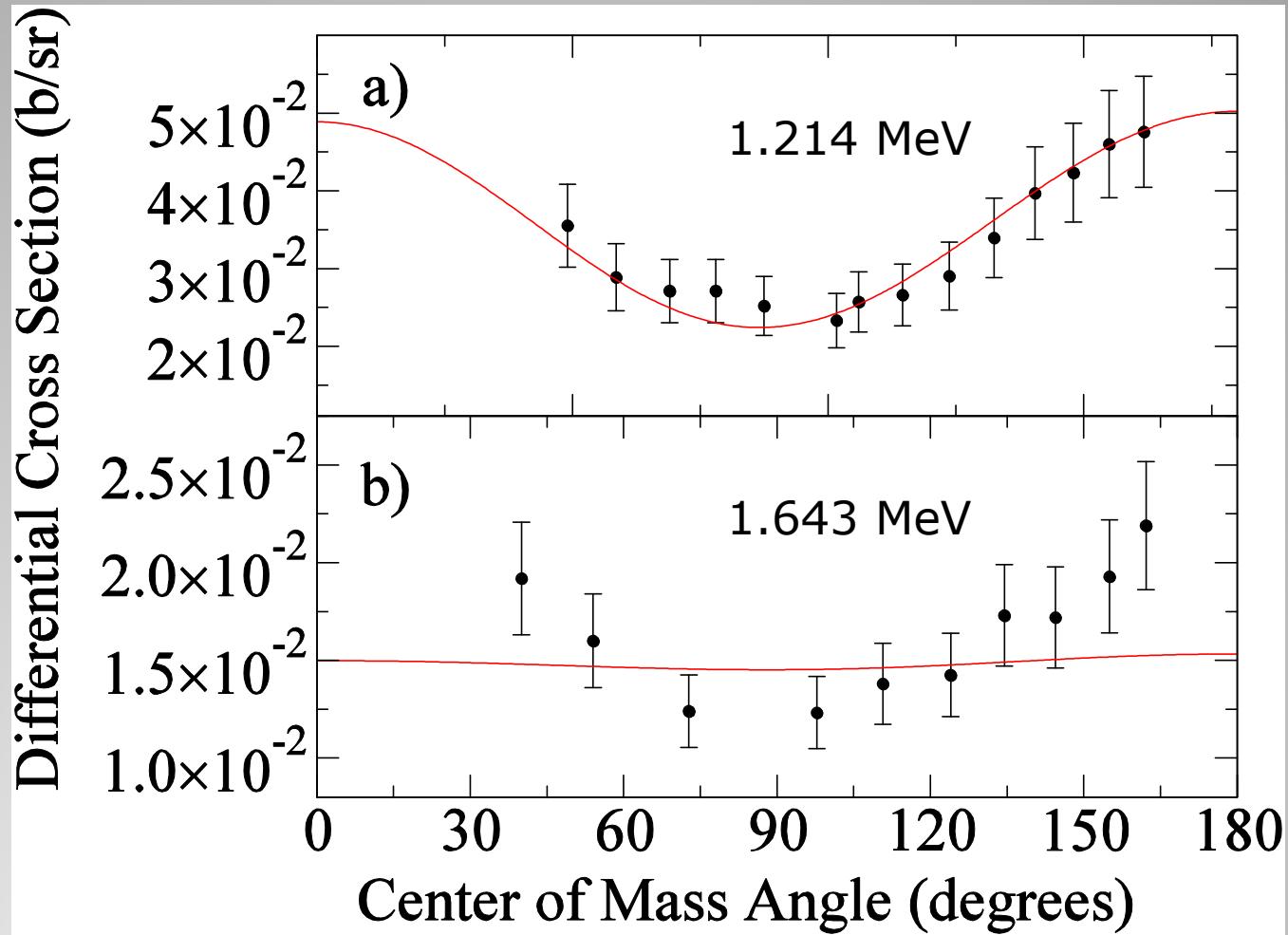
Bashkin *et al.* (1959)





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

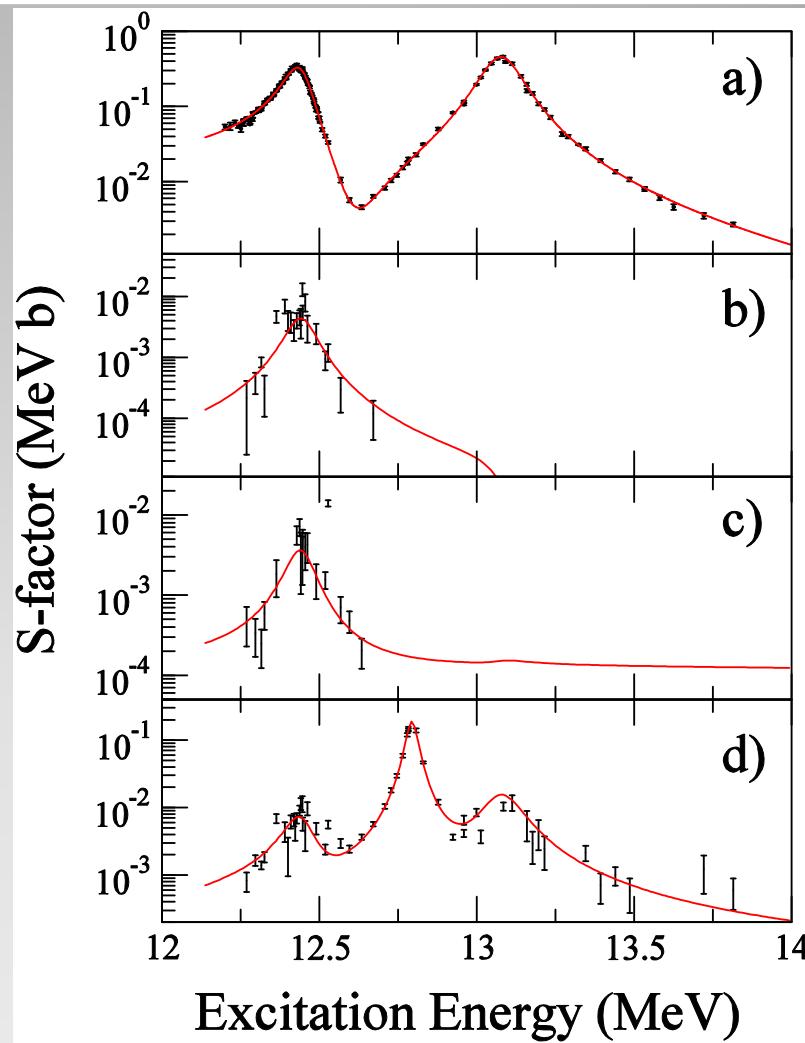
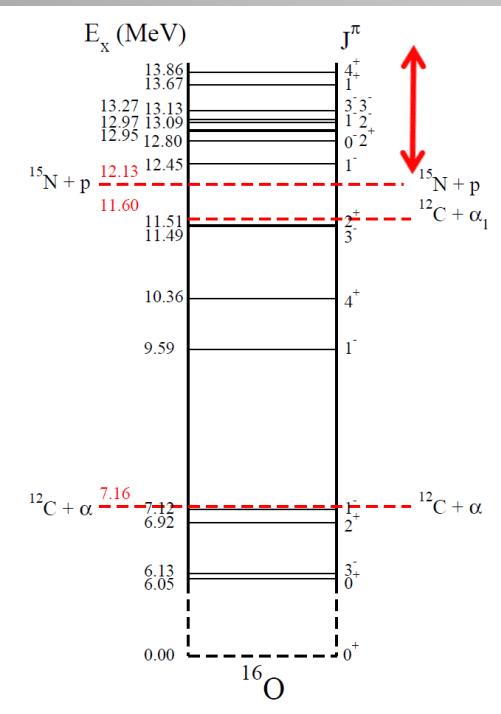
Bashkin *et al.* (1959)



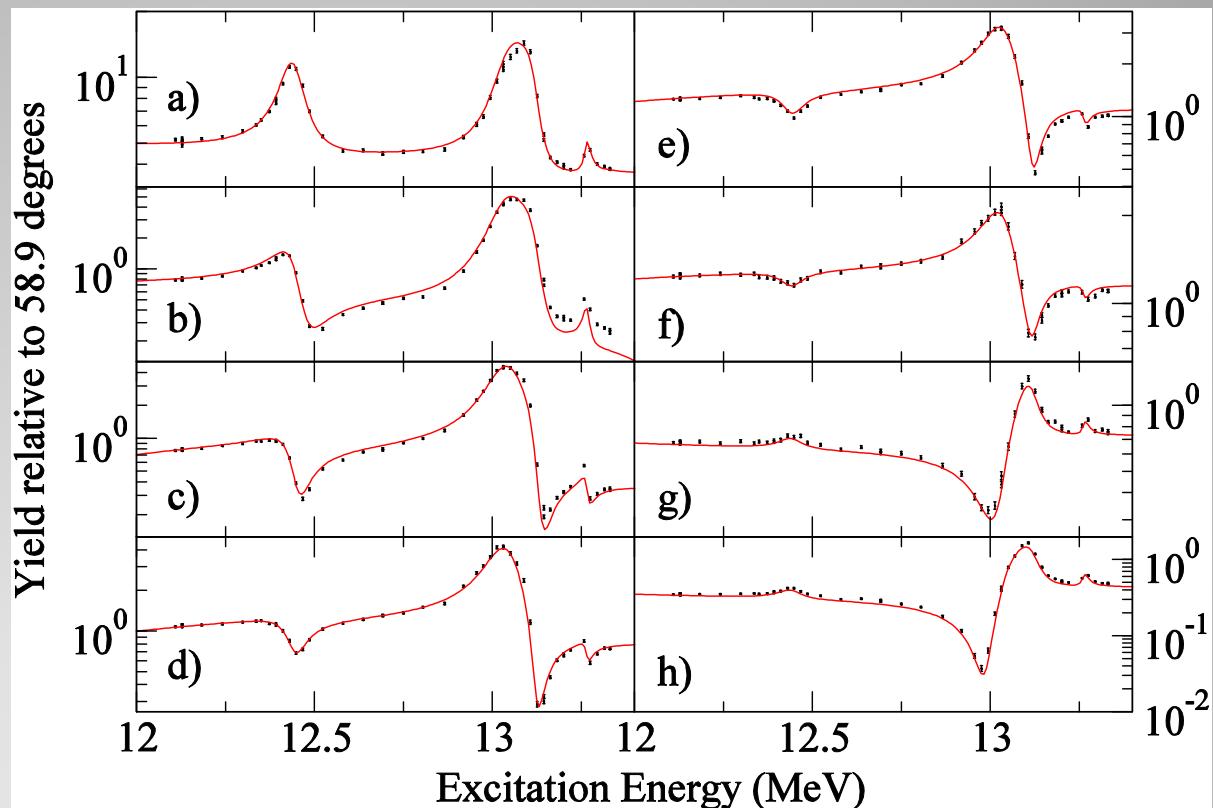
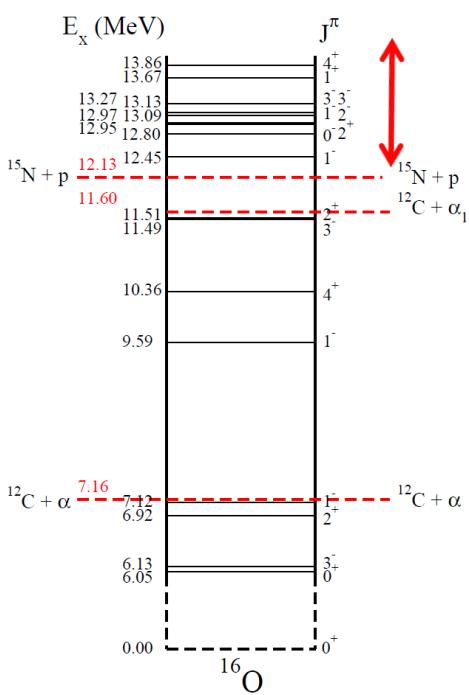
Bashkin *et al.* (1959)

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

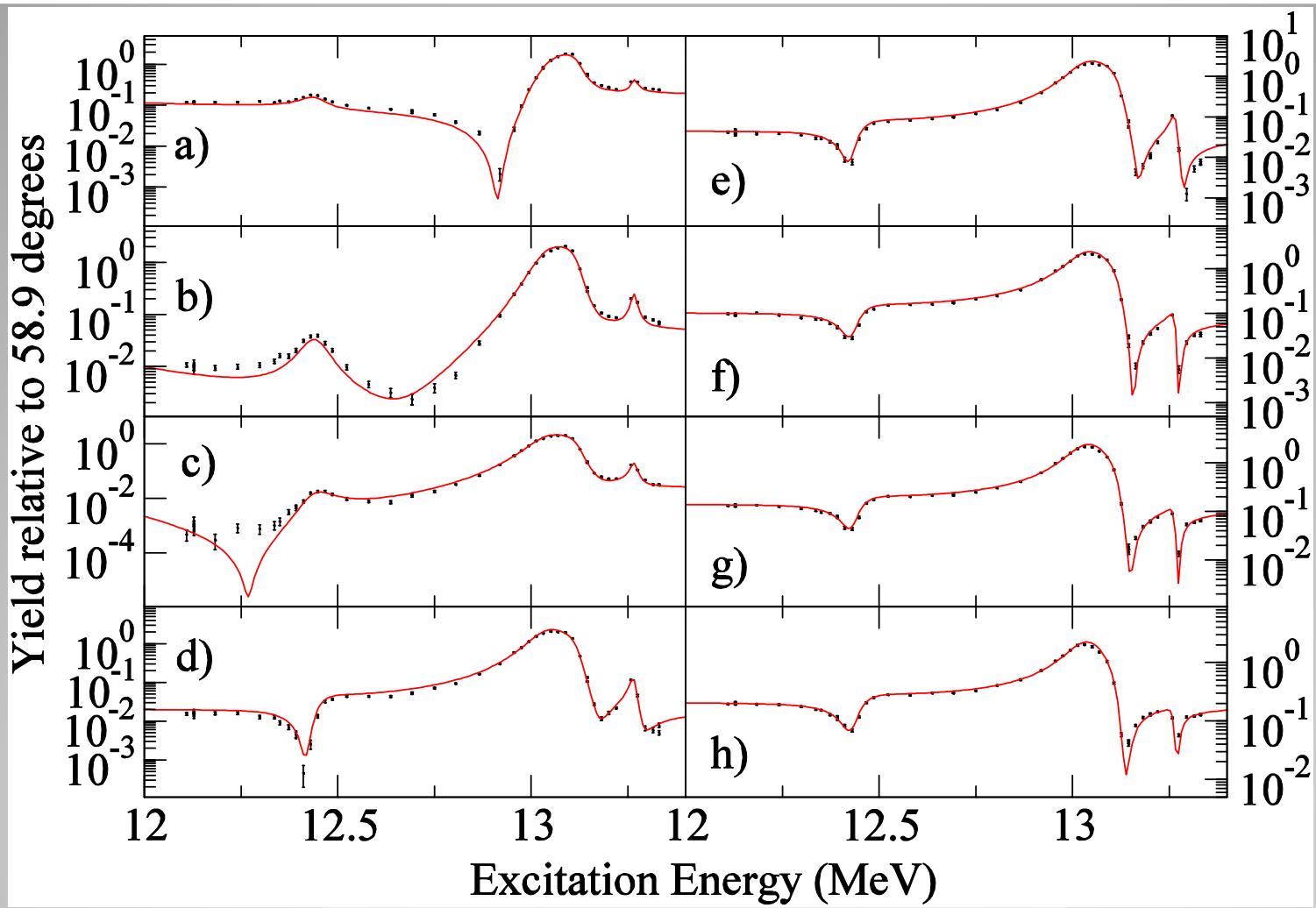
Unpublished Data



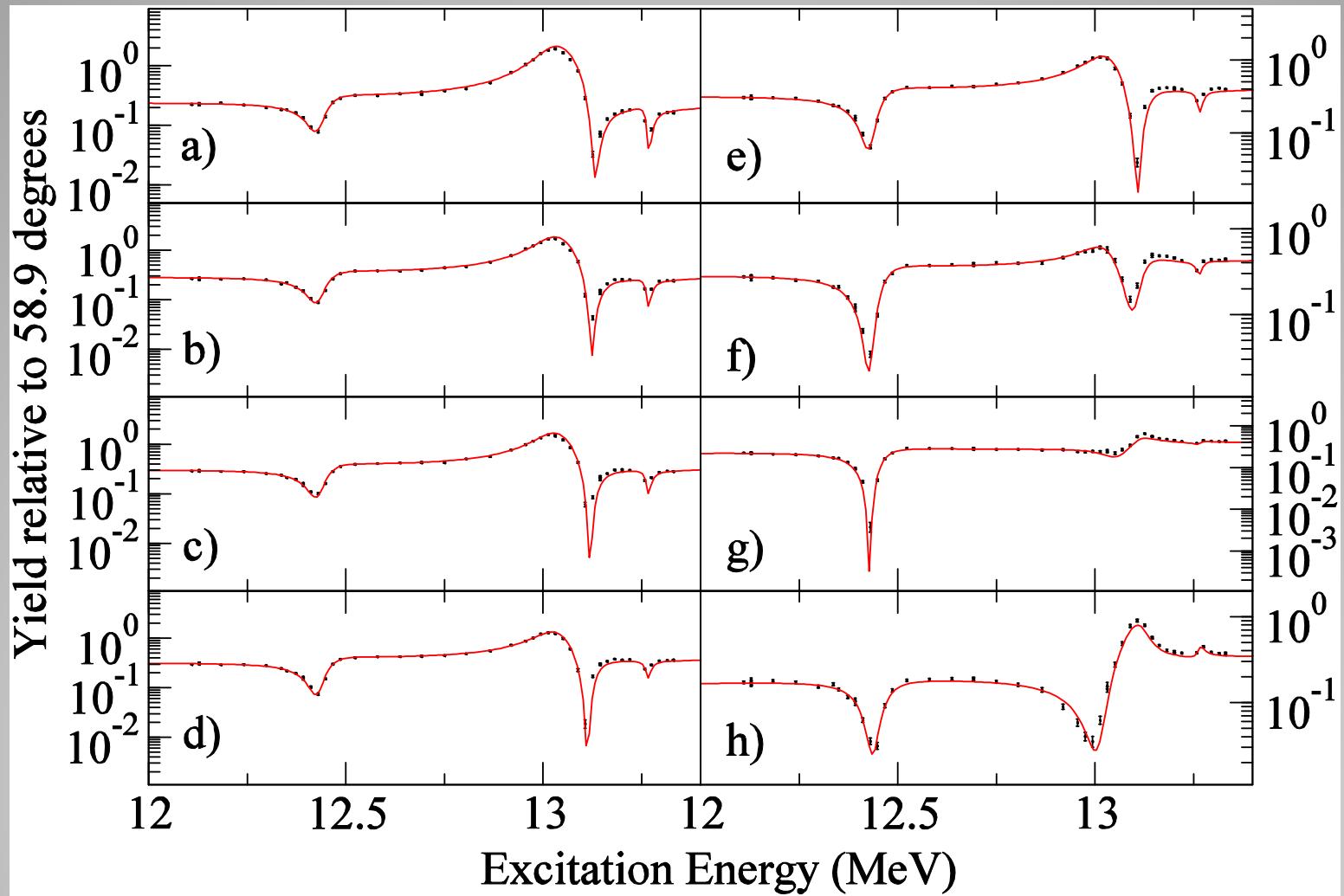
**$^{15}\text{N}(\text{p},\gamma)$ ground state, 6.05, 6.13,
and 7.12 MeV transitions, LeBlanc
et al. (2010) unpublished**



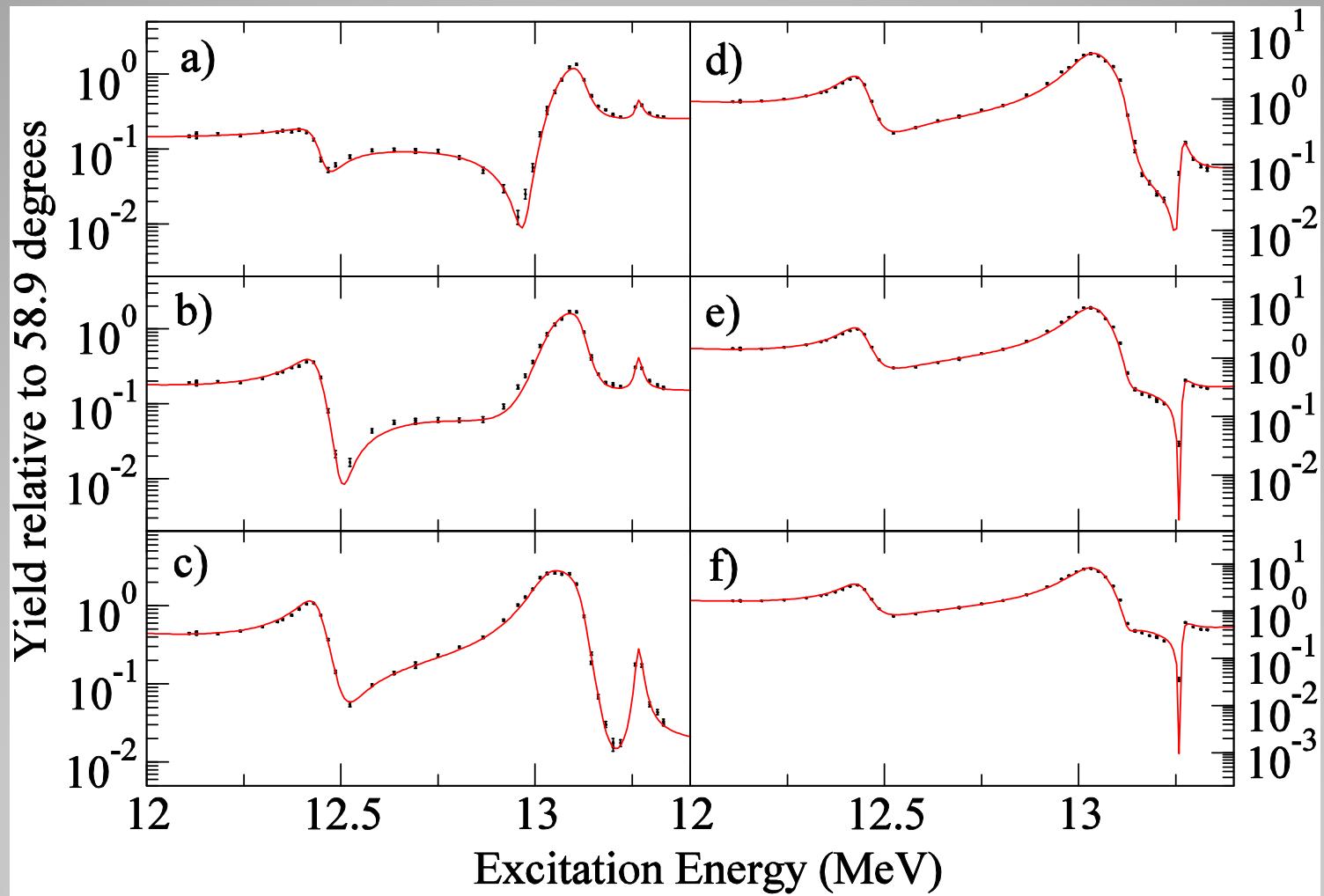
Tischhauser *et al.* (2009)
unpublished high energy data at 24, 33.9,
38.9, 43.9, 48.9, 54, 63.9, and 68.9 degrees



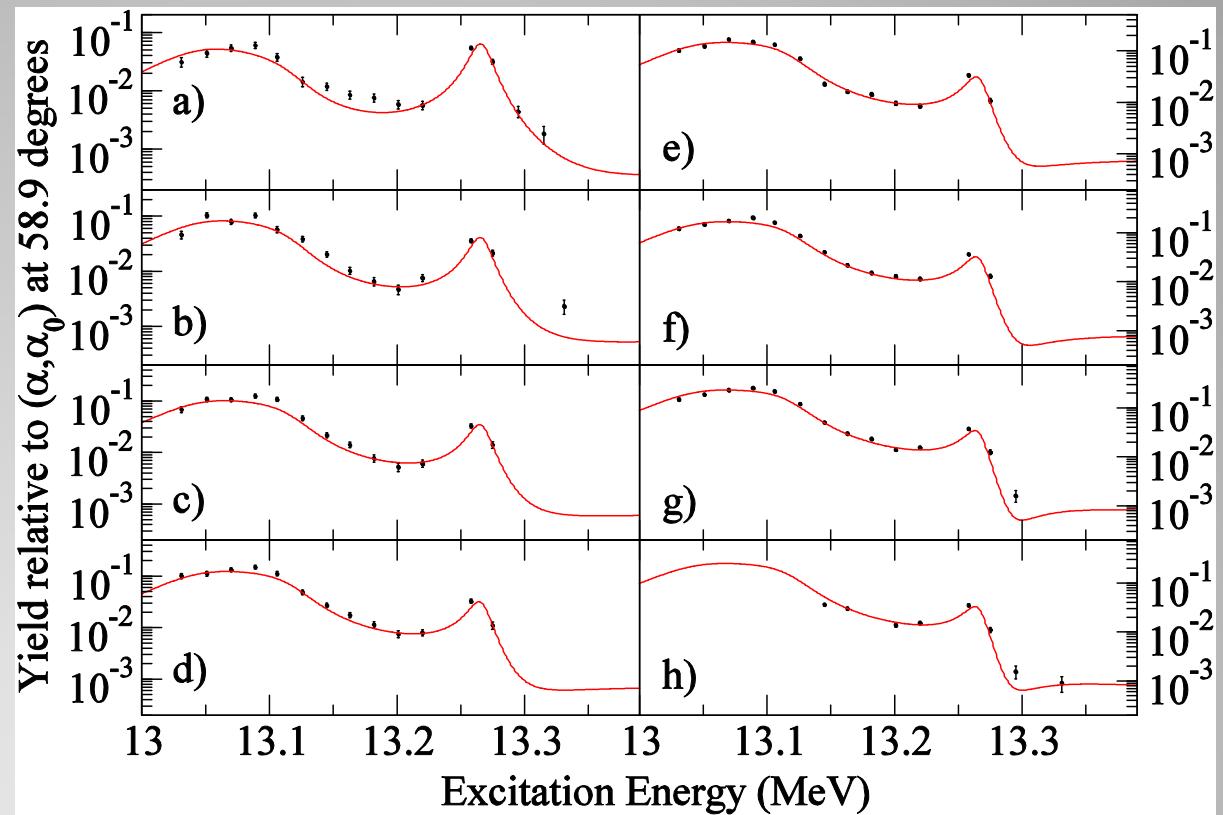
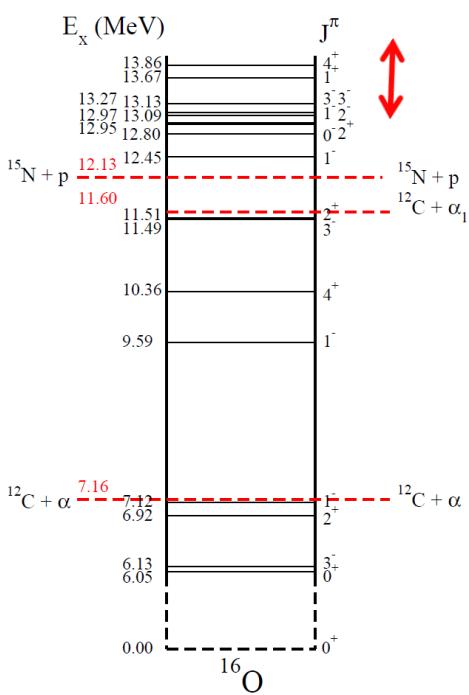
Tischhauser *et al.* (2009)
unpublished high energy data at 74, 75.8,
80.8, 84, 85.8, 89, 90.8, and 94 degrees



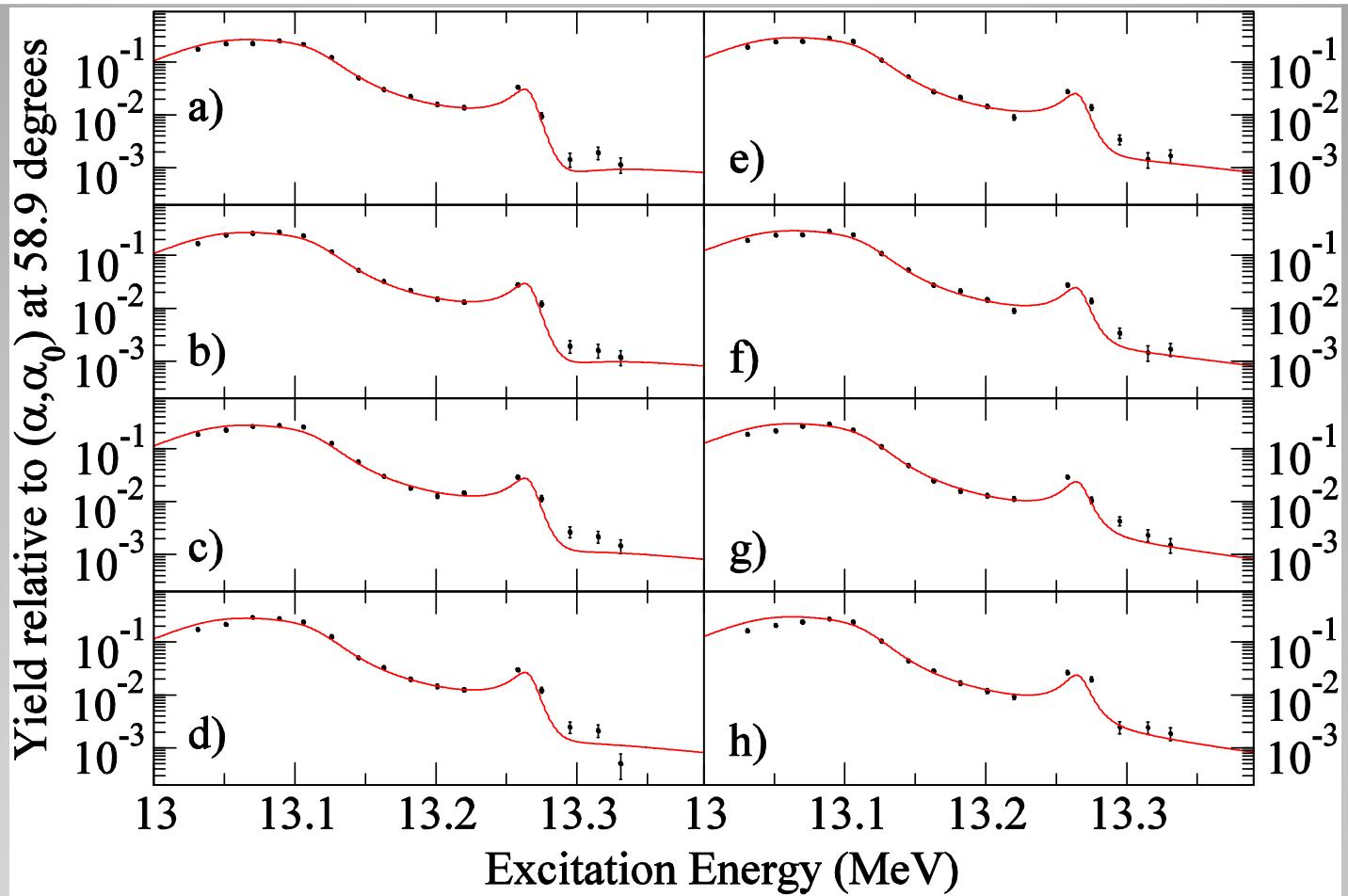
Tischhauser et al. (2009)
unpublished high energy data at 95.8, 99, 100.8, 103.9,
105.8, 110.8, 115.8, and 120.8 degrees



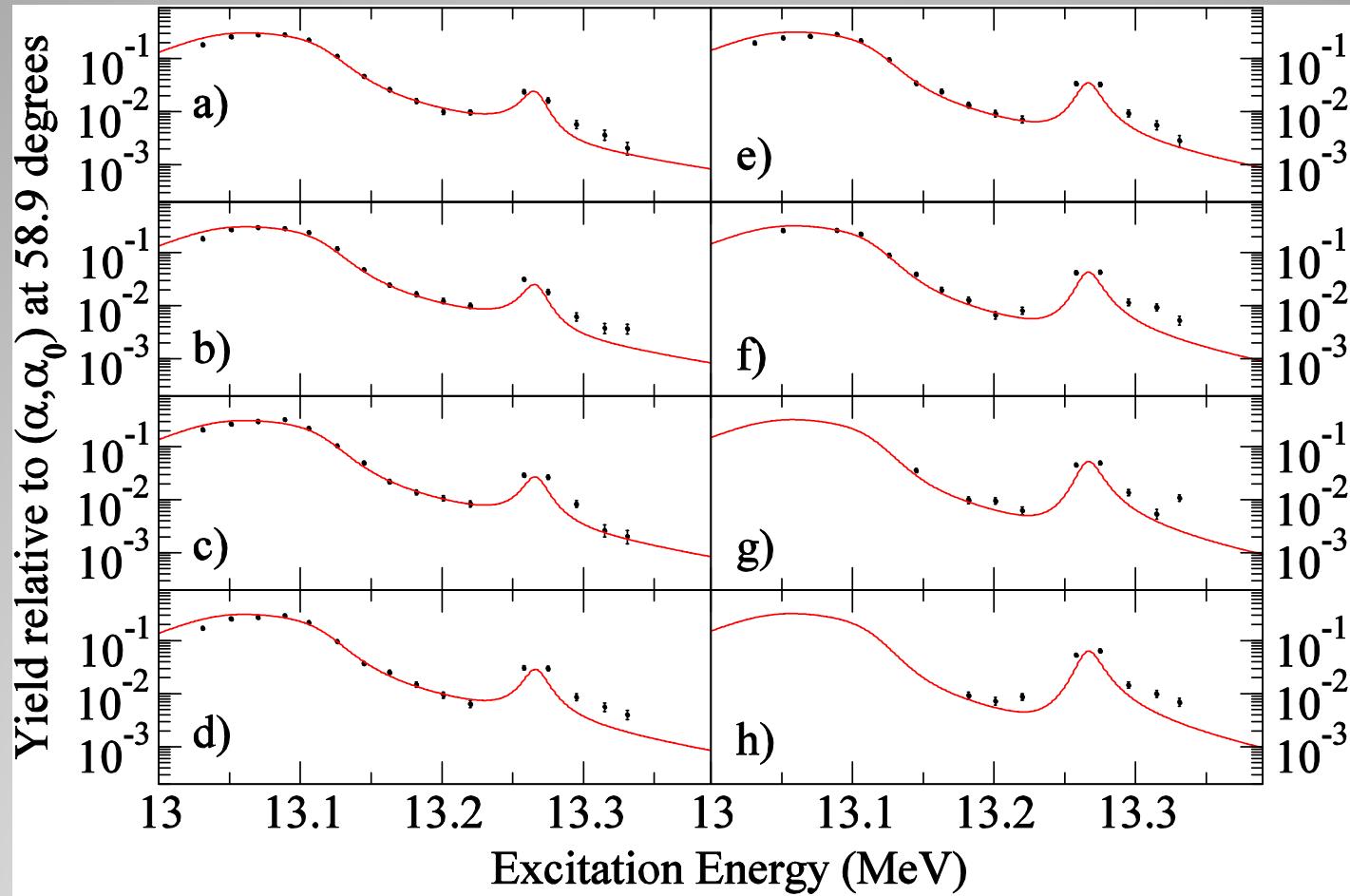
Tischhauser et al. (2009)
**unpublished high energy data at 125.8, 130.8, 140.8,
150.8, 160.8, and 165.9 degrees**



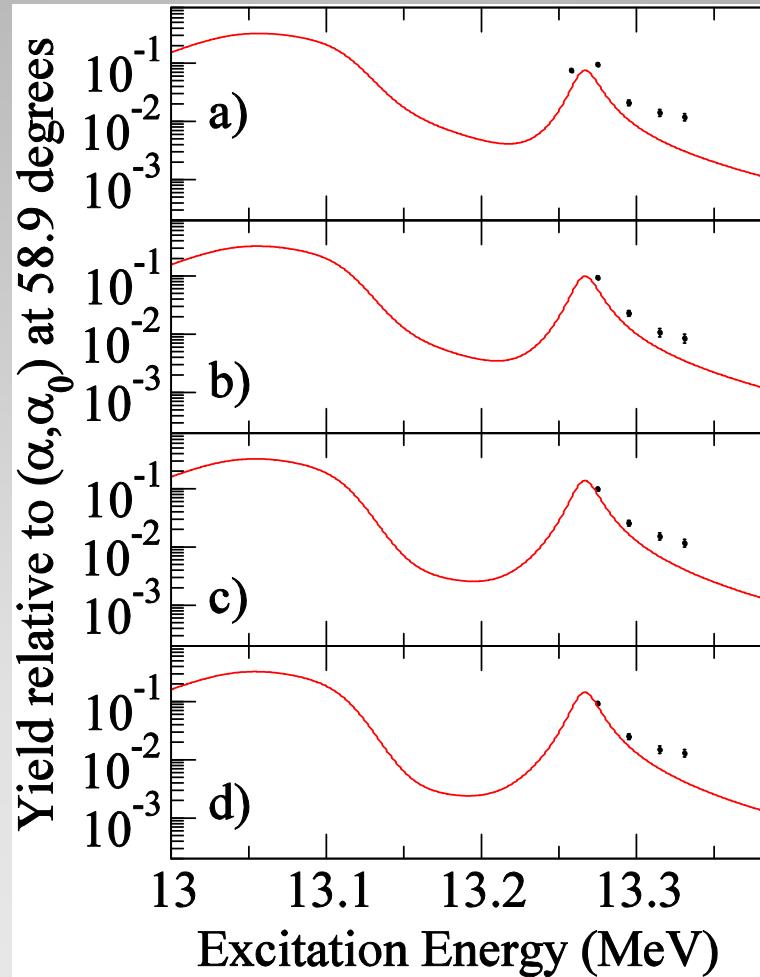
Tischhauser et al. (2009)
 unpublished high energy $^{12}\text{C}(\alpha, \text{p})$ data at 24,
 33.9, 38.9, 43.9, 48.9, 54, 68.9 and 74
 degrees



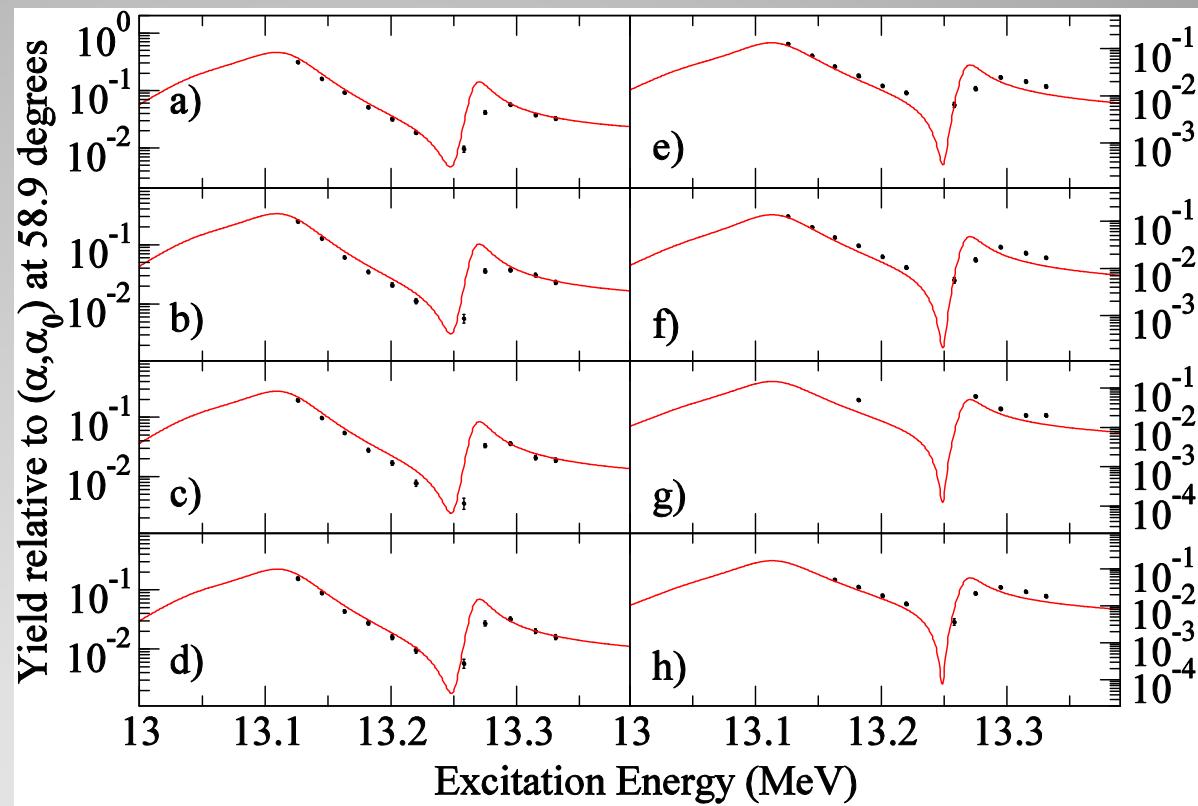
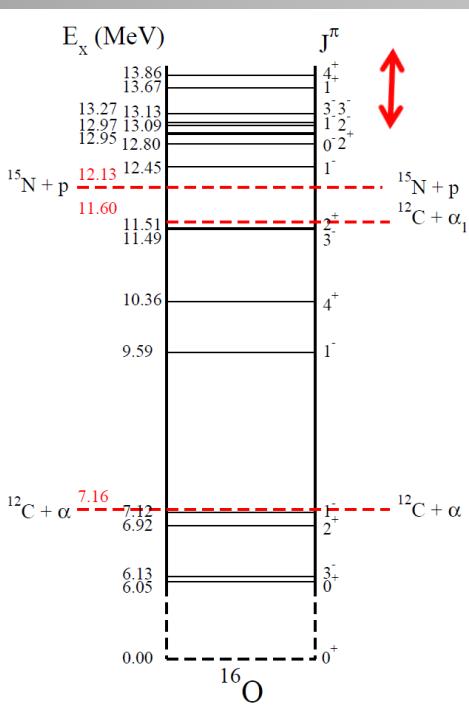
Tischhauser et al. (2009)
unpublished high energy $^{12}\text{C}(\alpha, \text{p})$ data
at 79, 80.8, 84, 85.8, 89, 90.8, 94, and 95.8
degrees



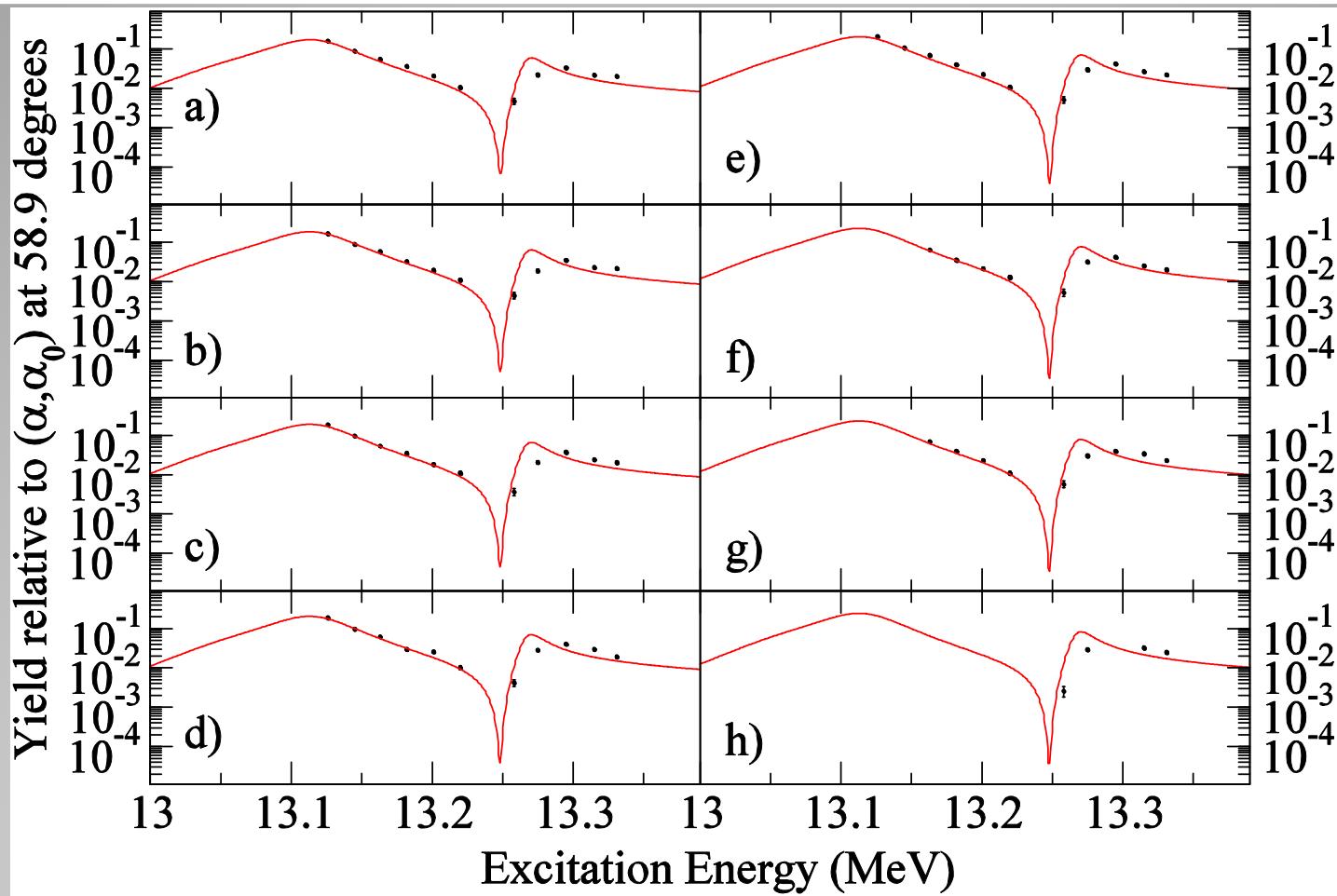
Tischhauser et al. (2009)
unpublished high energy $^{12}\text{C}(\alpha, \text{p})$ data
at 99, 100.8, 103.9, 105.8, 110.8, 115.8,
120.8, and 125.8 degrees



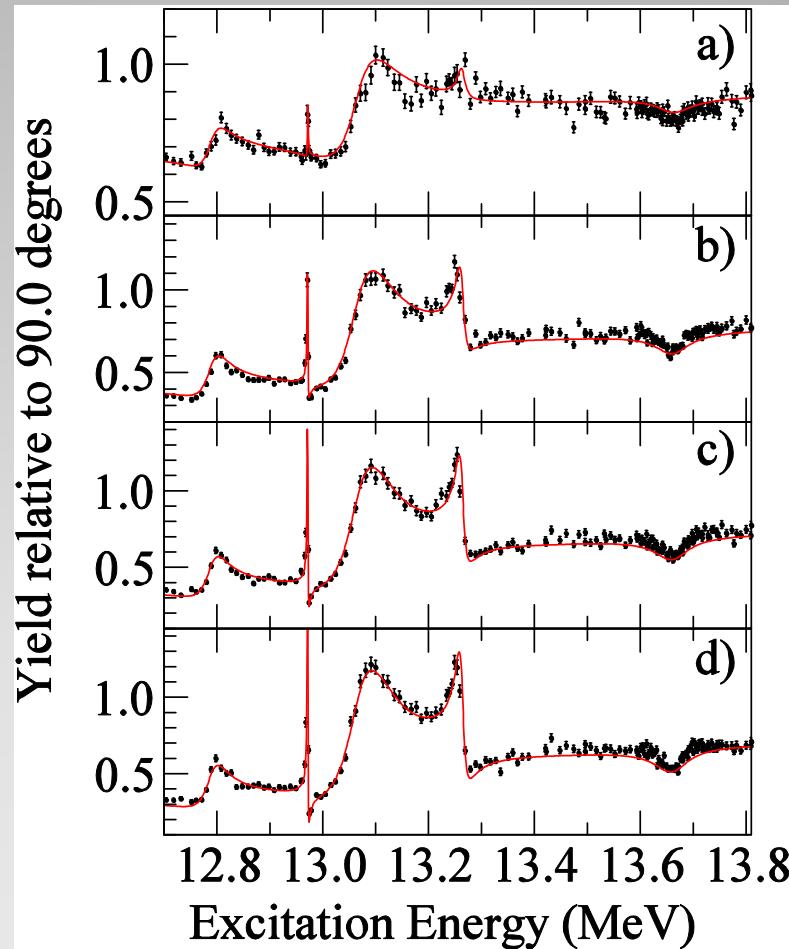
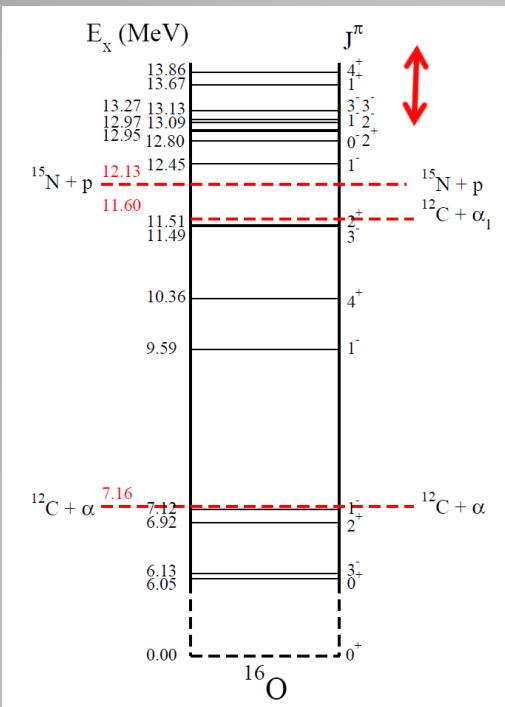
**Tischhauser *et al.* (2009)
unpublished high energy $^{12}\text{C}(\alpha, \text{p})$ data
at 130.8, 140.8, 150.8, and 160.8 degrees**



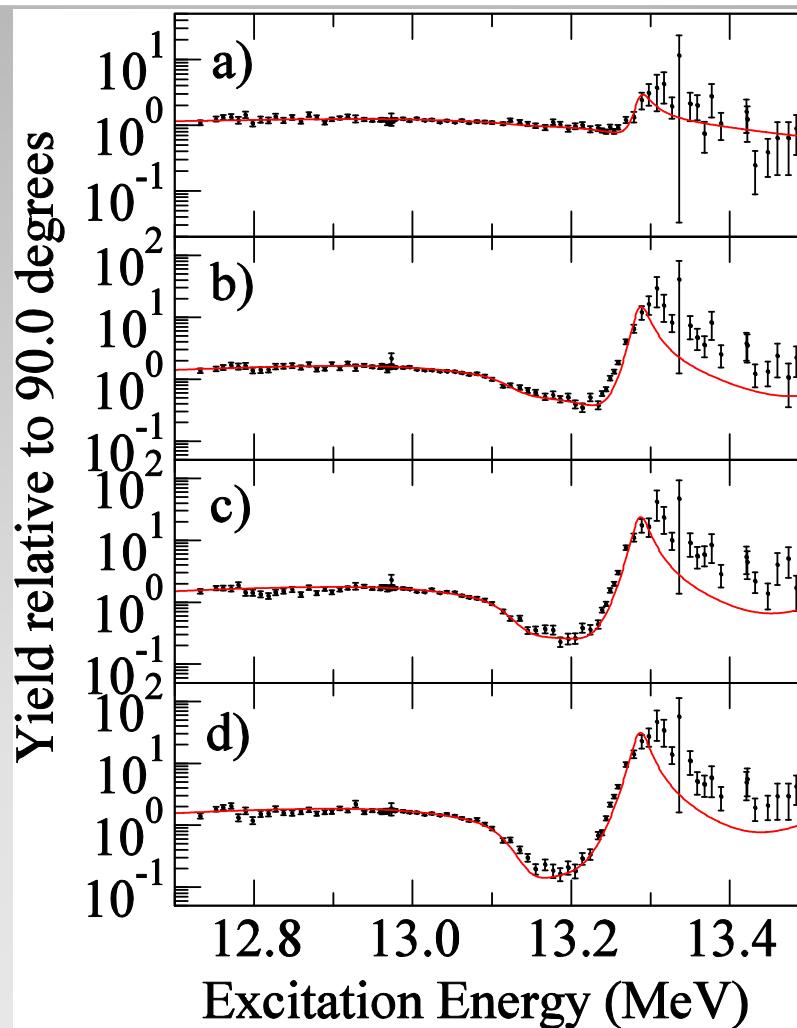
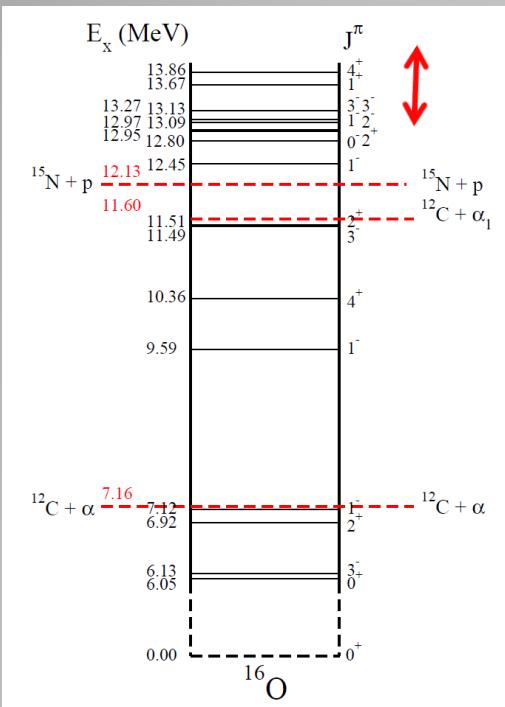
**Tischhauser *et al.* (2009)
unpublished high energy $^{12}\text{C}(\alpha, \alpha_1)$ data
at 24, 33.9, 38.9, 43.9, 63.9, 68.9, 74, and
79 degrees**



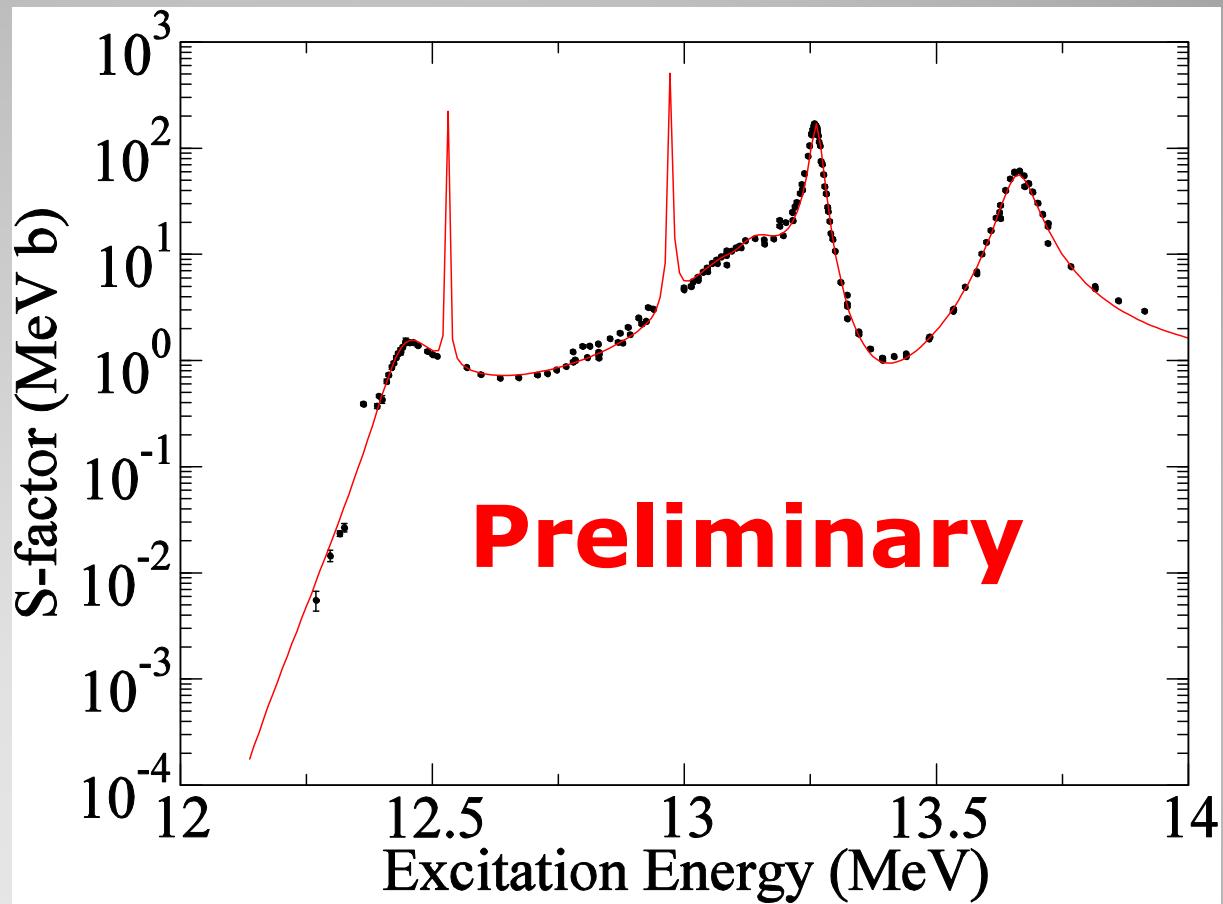
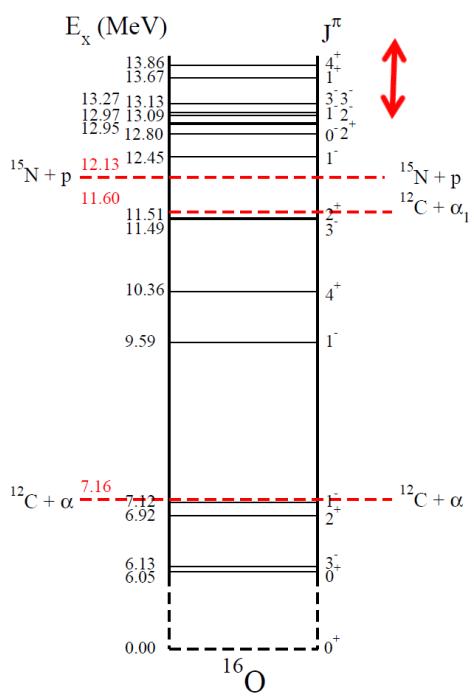
Tischhauser et al. (2009)
unpublished high energy $^{12}\text{C}(\alpha, \alpha_1)$ data
at 80.8, 84, 85.8, 89, 90.8, 94, 95.8, and 99
degrees



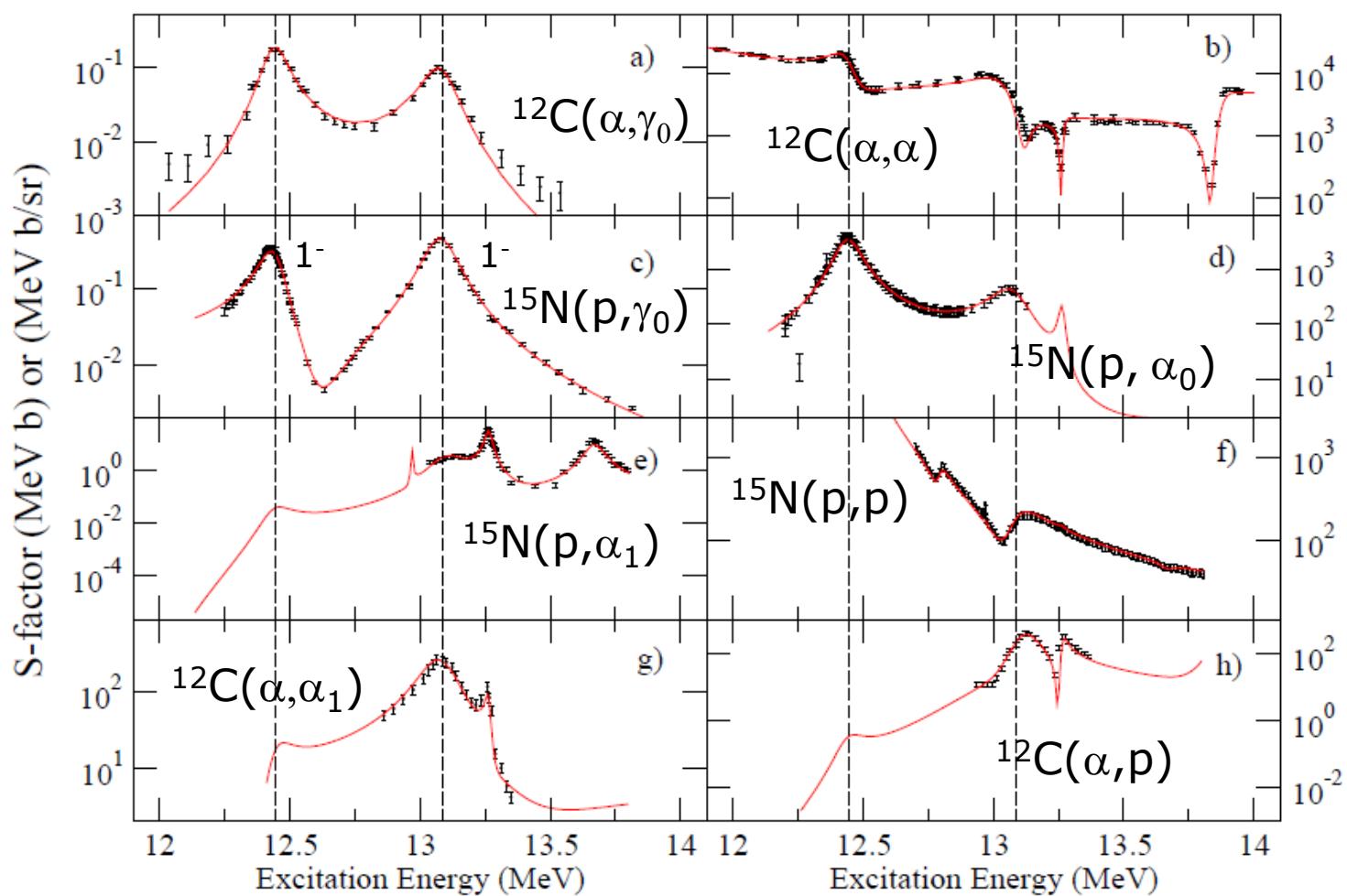
**$^{15}\text{N}(\text{p},\text{p})$ yield ratio to 90 degrees
105, 135, 150, and 165 degrees,
LeBlanc *et al.* (2012)**



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



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



Simultaneous Multiple Entrance/Exit Channel *R*-matrix Analysis

- 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 $^{-1/2}$
- $S(10 \text{ keV}) = 39.0(3.6)$ keV b (10%)
- Uncertainty in $S(0)$ improved from 15% to < 10%
- BGP is largest source of uncertainty

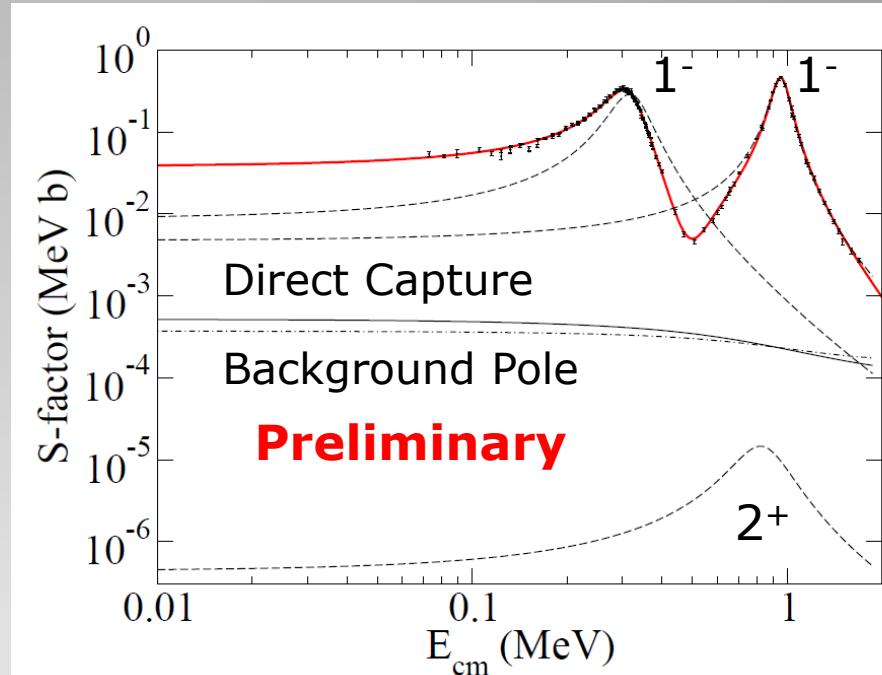


TABLE III. Summary of previous results for extrapolated $S(0)$ values.

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

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

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 $^{15}\text{N}(\text{p},\gamma)$, uncertainty < 10%

Conclusion



The Joint Institute for Nuclear Astrophysics

AZURE R-Matrix Program

[Contact Us](#) | [Search](#) | [Site Map](#) | [Virtual Journal](#) | [Tools & Data](#) | [Highlights](#) | [Jobs](#) | [Events](#) | [Sign Up](#)

[About AZURE](#)

[Documentation](#)

[Example Fits](#)

[Downloads](#)

[User Forum](#)

[Contact Us](#)

[Developers](#)

[Administrators](#)

About AZURE

AZURE is an R-Matrix minimization code developed under the support of the Joint Institute for Nuclear Astrophysics (JINA). The code has been designed specifically for the needs of the Nuclear Astrophysics community and has been optimized for low energy charged particle reactions relevant to stellar nucleosynthesis. AZURE is ideal for the analysis of complex multi-level multi-channel reactions with an interface constructed for ease of use and flexibility. In addition to the compound nucleus mechanism, AZURE also supports the analysis of reactions containing direct capture components.

Versions of Internet Explorer before 8.0 are known to have some compatibility problems when rendering this website.

[Copyright © 2002-2011 JINA](#) | [Disclaimer](#) |

Thank You! azure.nd.edu

NSF Grant No. Phys-0758100 and JINA Grant No. Phys-0822648