



The $^{12}\text{C}(^{12}\text{C},n)^{23}\text{Mg}$ Reaction: A Potential Neutron Source for the Weak S-Process

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Extremes of Density and Temperature: Cosmic Matter in the Laboratory

ExtreMe Matter Institute EMMI

EMMI-JINA Workshop
Nucleosynthesis beyond iron
and the lighter element primary process

GSI, Darmstadt, Germany
October 10-12, 2011

Key Topics

- Observational evidence of a stellar LFPP from UMP stars
- Showing approximately large ^{54}Fe - ^{52}Cr abundances
- LFPP contribution to the solar system abundances
- Are the solar LFPP and stellar LFPP the same process?
- Possible astrophysical scenarios to create LFPP abundances
- Main nuclear physics uncertainties affecting LFPP nucleosynthesis
- Constraints from galactic chemical evolution models

Associated Event
John Cowan and the low metallicity galaxy

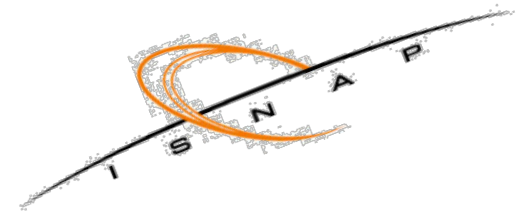
Information
www.gsi.de/conferences/emmi/LEPP2011

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More about JINA
www.jina.org

More about EMMI
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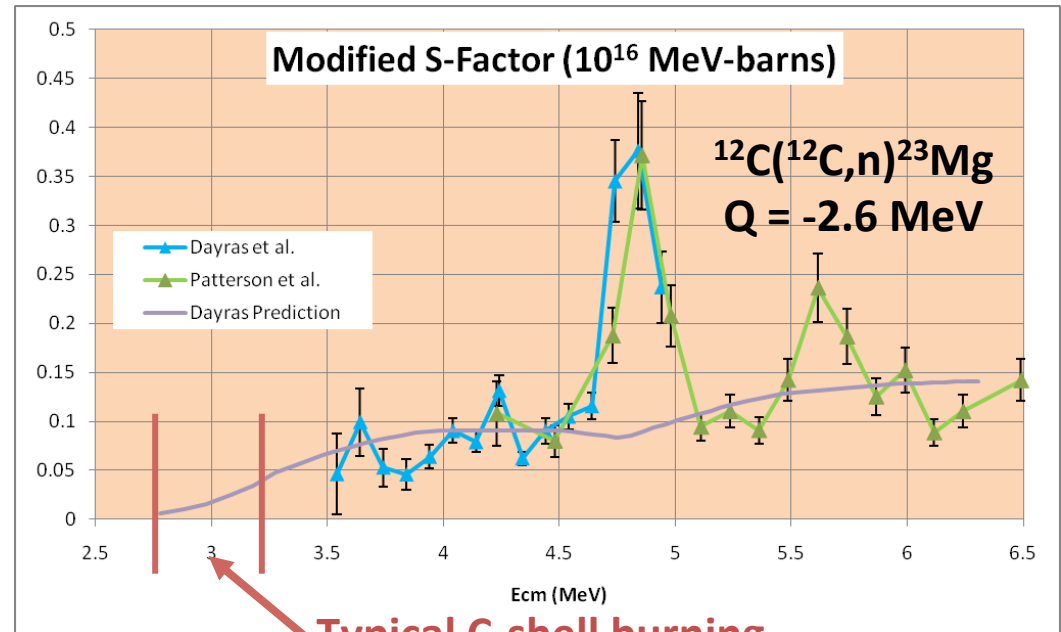


Outline

- Motivation
 - Uncertain reaction rate
 - Synthesis of light elements above iron
- Measurement of $^{12}\text{C}(^{12}\text{C},n)^{23}\text{Mg}$
 - Results & Challenges
- Improved Extrapolation—Isospin Symmetry
 - Measurement of $^{12}\text{C}(^{12}\text{C},p)^{23}\text{Na}$
- Effects on the Astrophysical Reaction Rate
- Conclusions

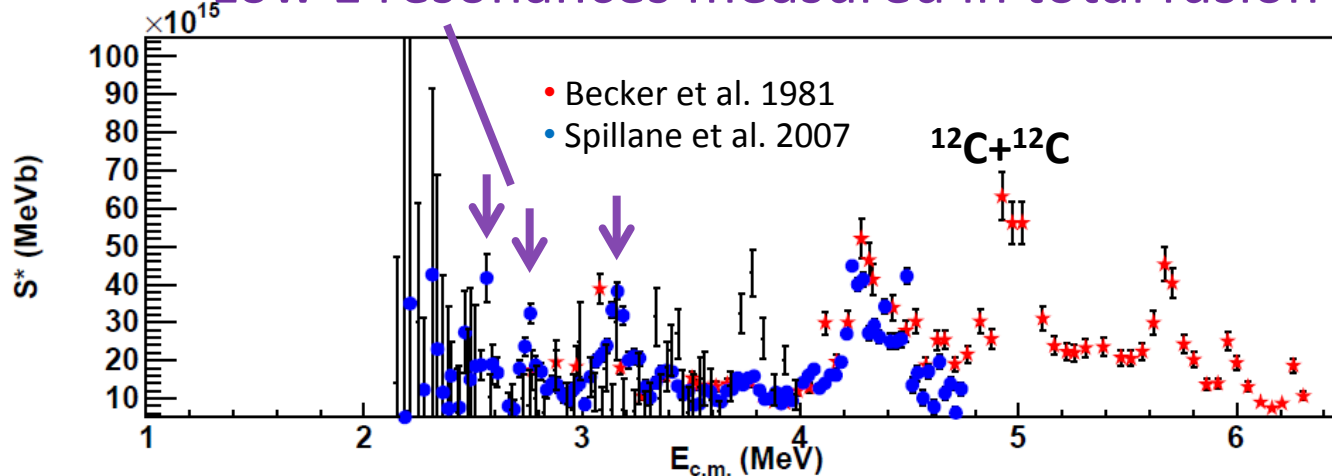
Uncertainty in Reaction Rate

- Resonances form important contribution to excitation function
- Resonance structure continues to lowest energies
- Current rate cannot account for resonances

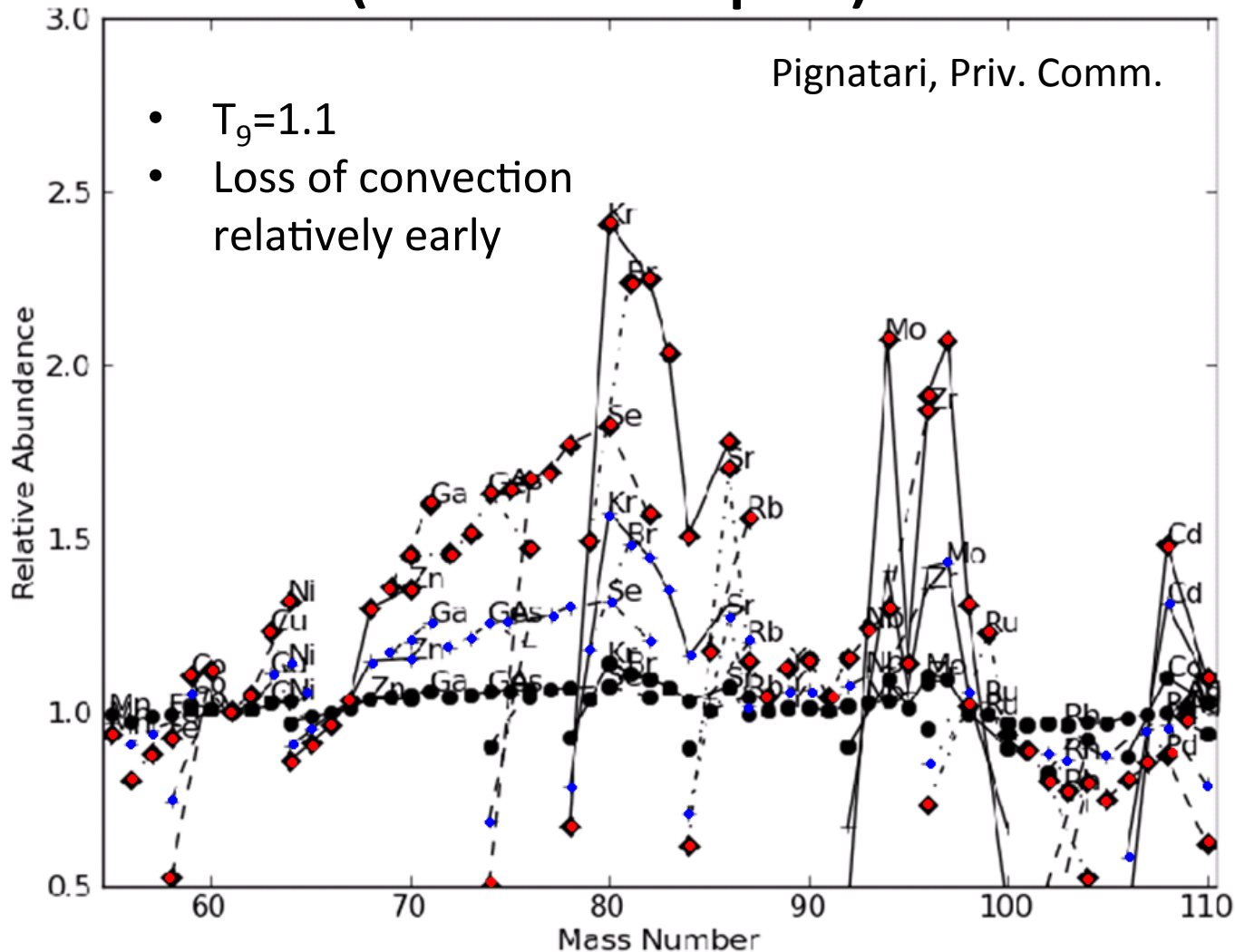


Typical C-shell burning

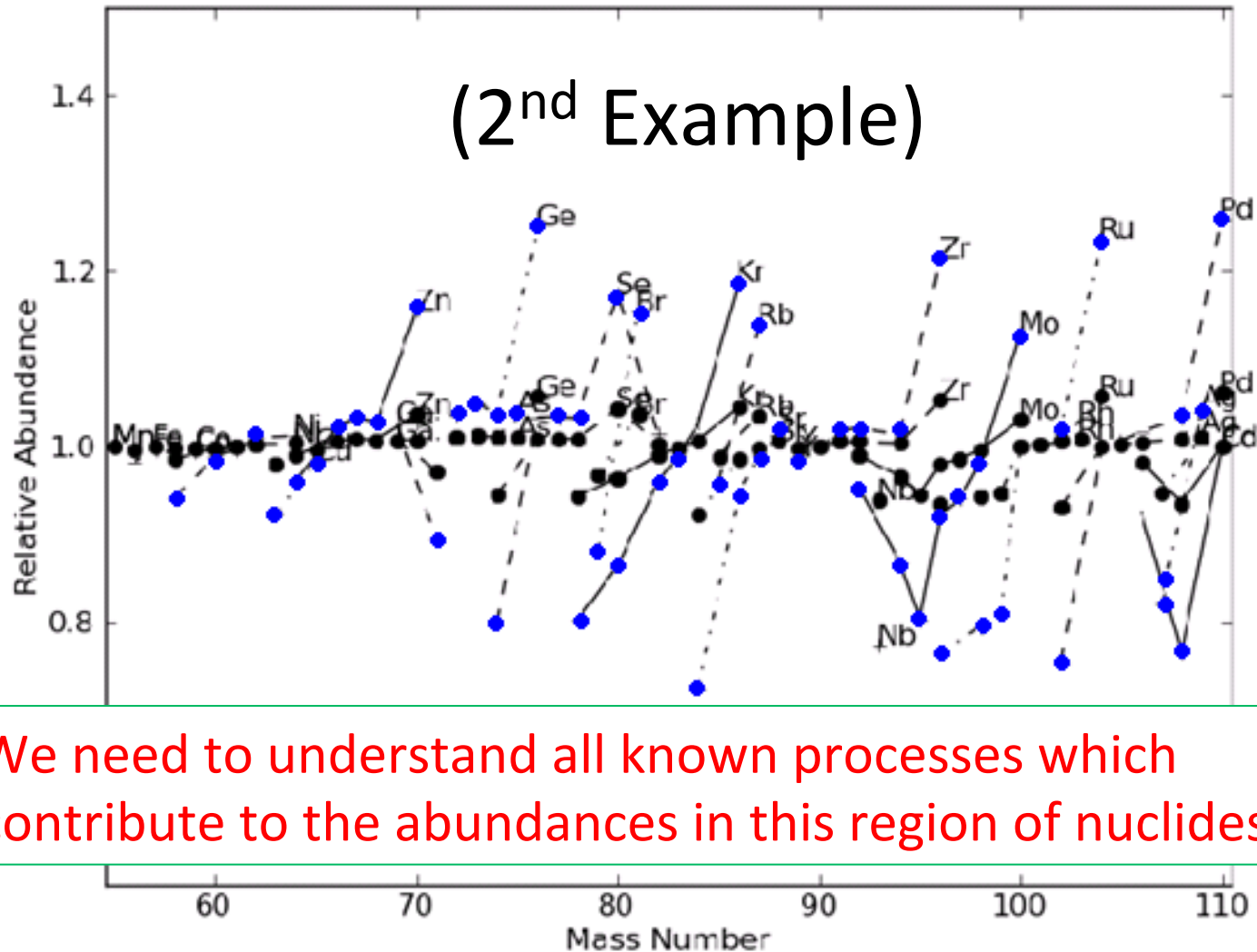
Low E resonances measured in total fusion x-section



Effect on Carbon-Shell Yields (1st example)



$^{12}\text{C}(^{12}\text{C},n)$ rate varied by factors 2, 5, 10



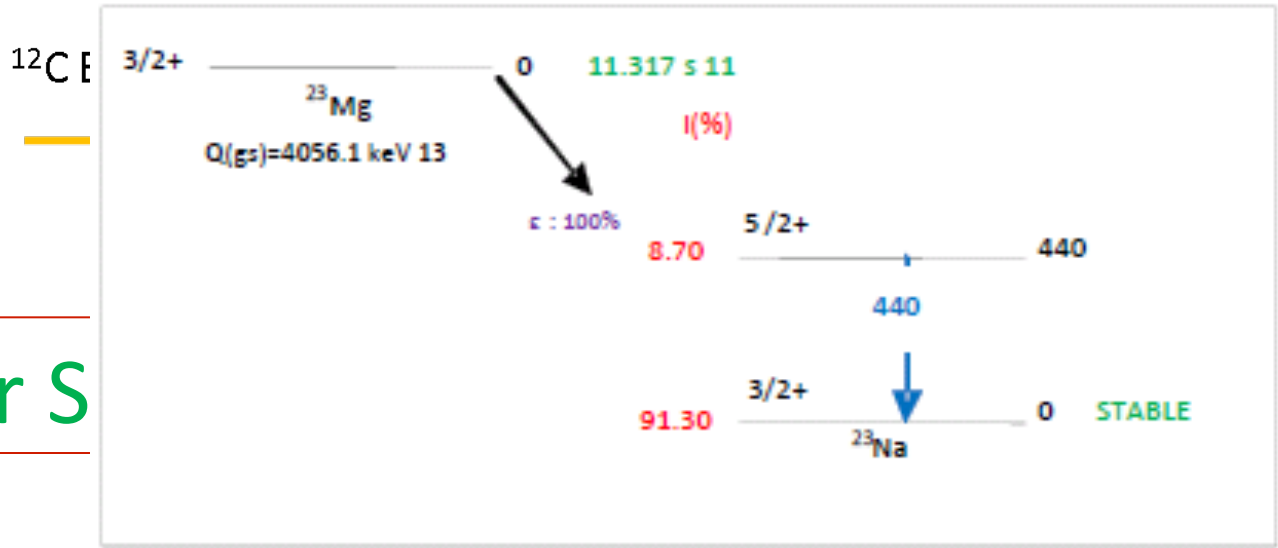
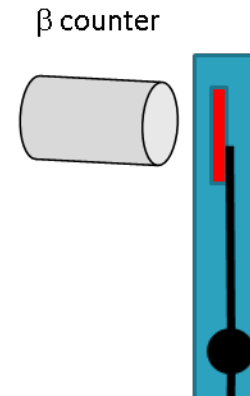
We need to understand all known processes which contribute to the abundances in this region of nuclides!

- Late C shell—convective until SN explosion
- Low initial C due to mixing with previous C-shells
- Initial $T_9 \sim 1.0$ peaking to 1.36 near end
- 2, 5 factor increase over Dayras rate

Measuring $^{12}\text{C}(^{12}\text{C},n)^{23}\text{Mg}$

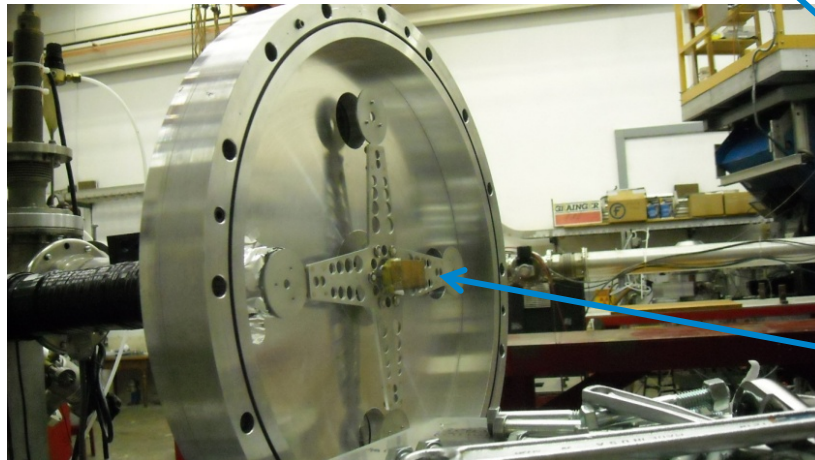
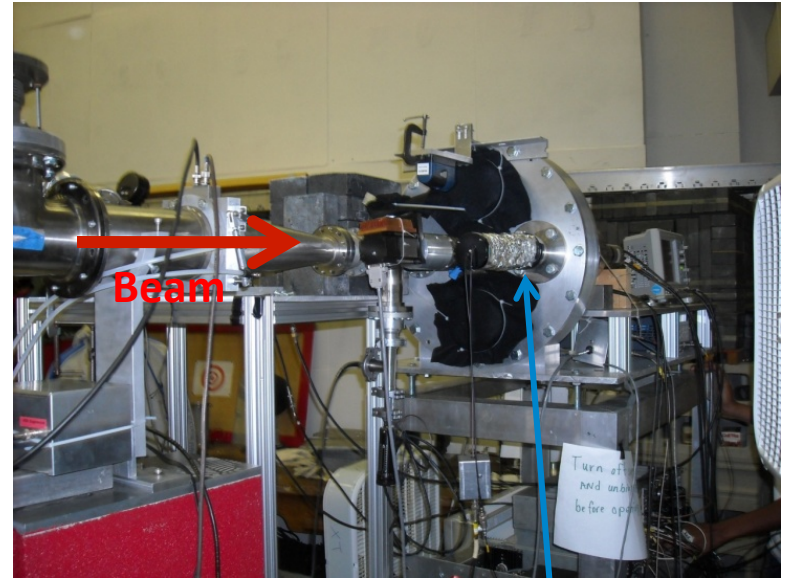
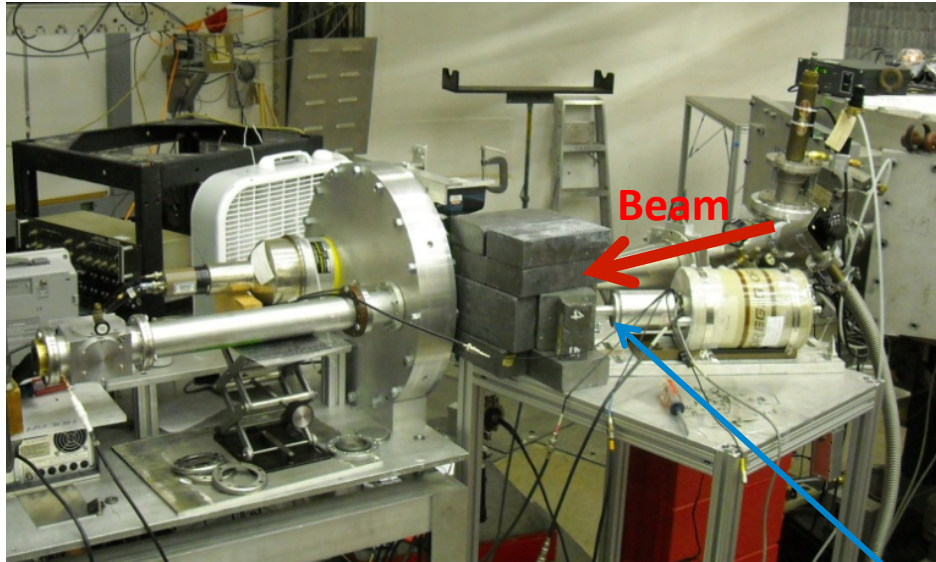
- Patterson et al. 1969: thin target, count β^+
- Dayras et al. 1977: thin target, count γ 440 & 511 keV
- Notre Dame 2011: thin & thick targets, count β^+

Counting Station



Our S

Experiment at Notre Dame



Ge Detector

β Counter

Catcher Wheel

Experimental Results

Low Energy Difficulties

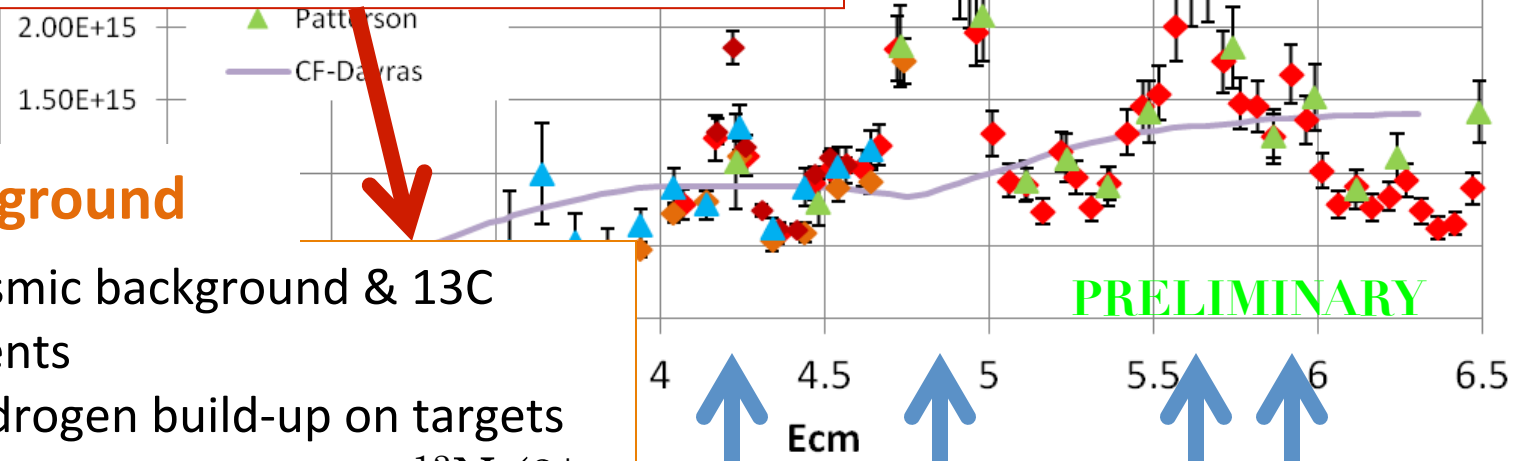
- Low cross-section!
 - 100 nb @ 3.5 MeV
 - 10 nb @ 3.2 MeV
 - 1 nb @ 3.0 MeV
- Yield = 10^{-15} events/ ^{12}C @ 1nb
- At ND, beam intensity = 10^{13} $^{12}\text{C}/\text{s}$ 🙄

S-Factor (MeV b)

- Measured finer step size over large energy range
- Consistent with others

Background

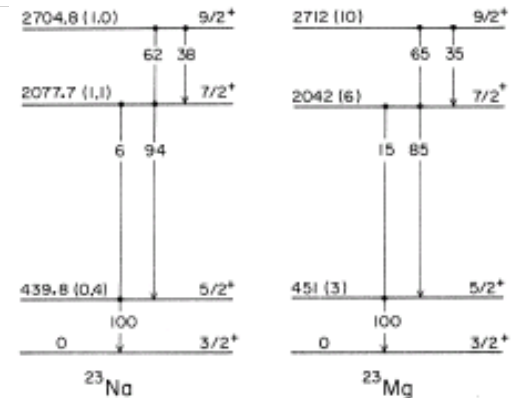
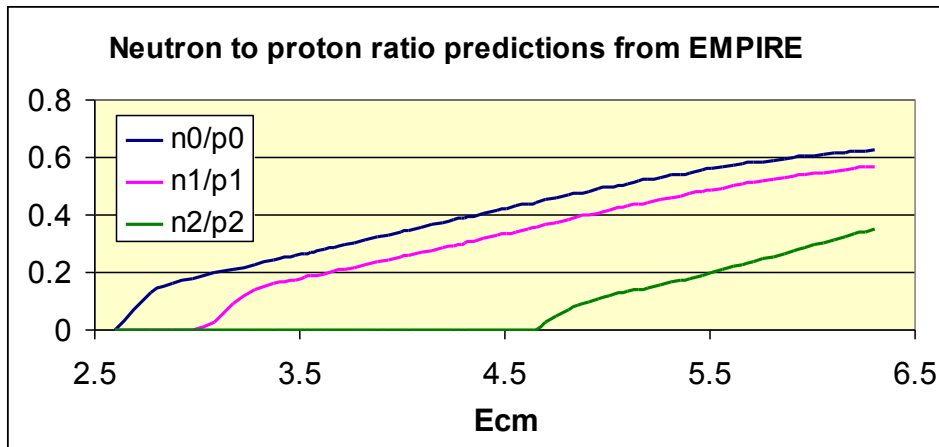
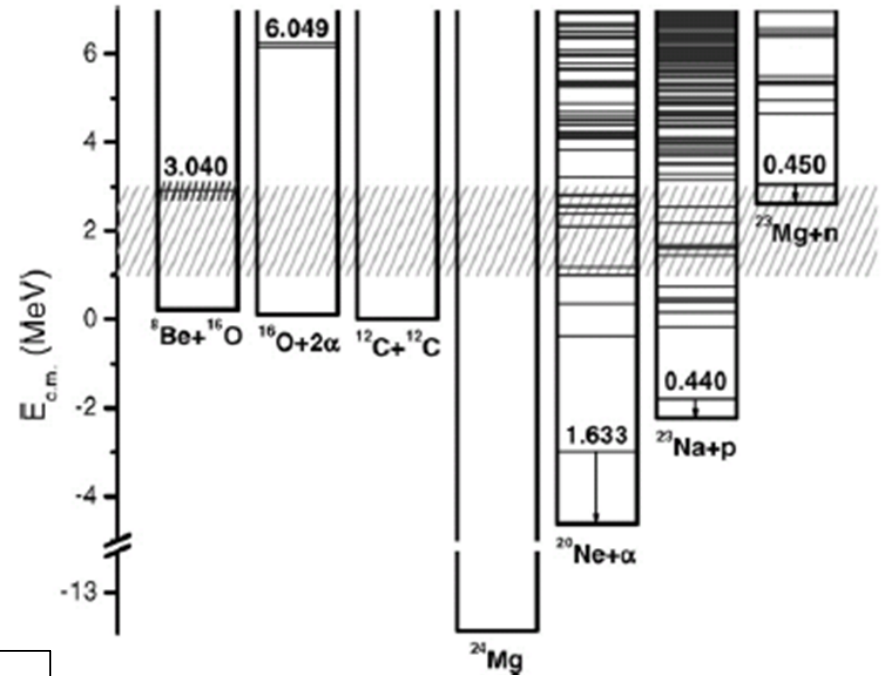
- Cosmic background & ^{13}C events
- Hydrogen build-up on targets
 - Large x.s. \rightarrow p, n, ^{13}N (β^+ emitter) 🙄



Note consistent resonance energies

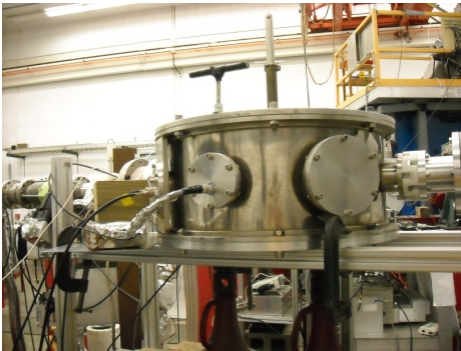
Mirror Symmetry: A New Way to Extrapolate

- Extrapolation based on mirror system $^{12}\text{C}(^{12}\text{C},p)$
 - Lower energy measurements ($Q=+2.2\text{MeV}$)
 - Structure effects should be same for both
- Use statistical model to calculate ratio $\sigma(n_i)/\sigma(p_i)$

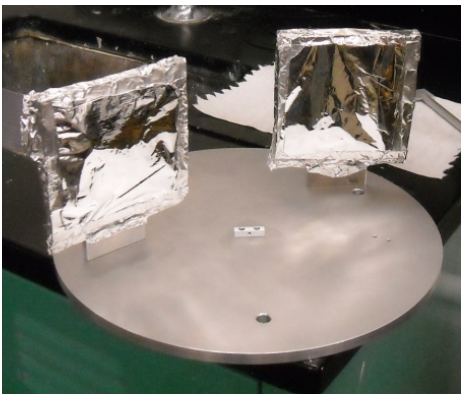


$^{12}\text{C}(^{12}\text{C},p_i)$ Measurements!

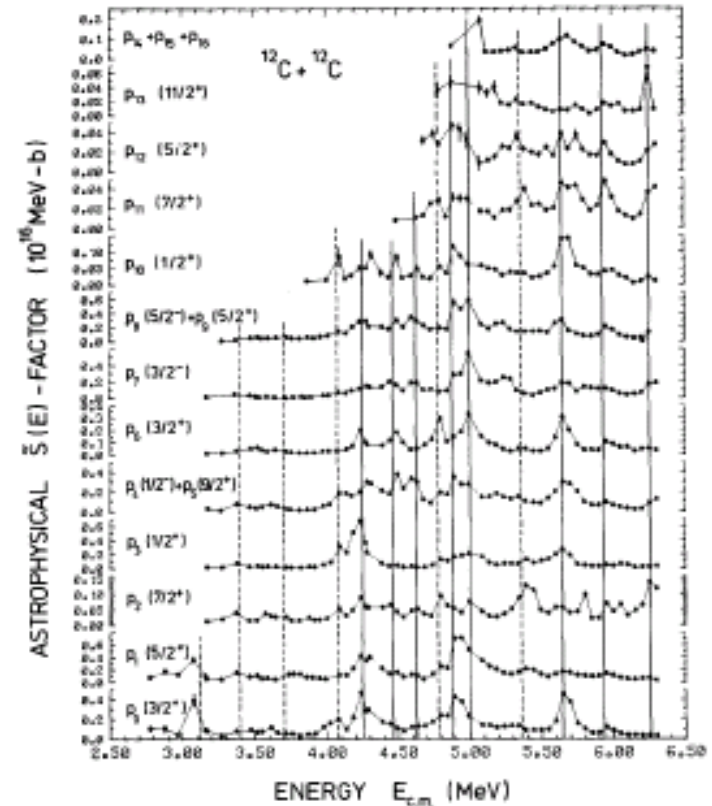
- Use Becker et al. 1981 measurements for extrapolation
- Recent measurements at ND to provide check for Becker et al.



Detector chamber at ND

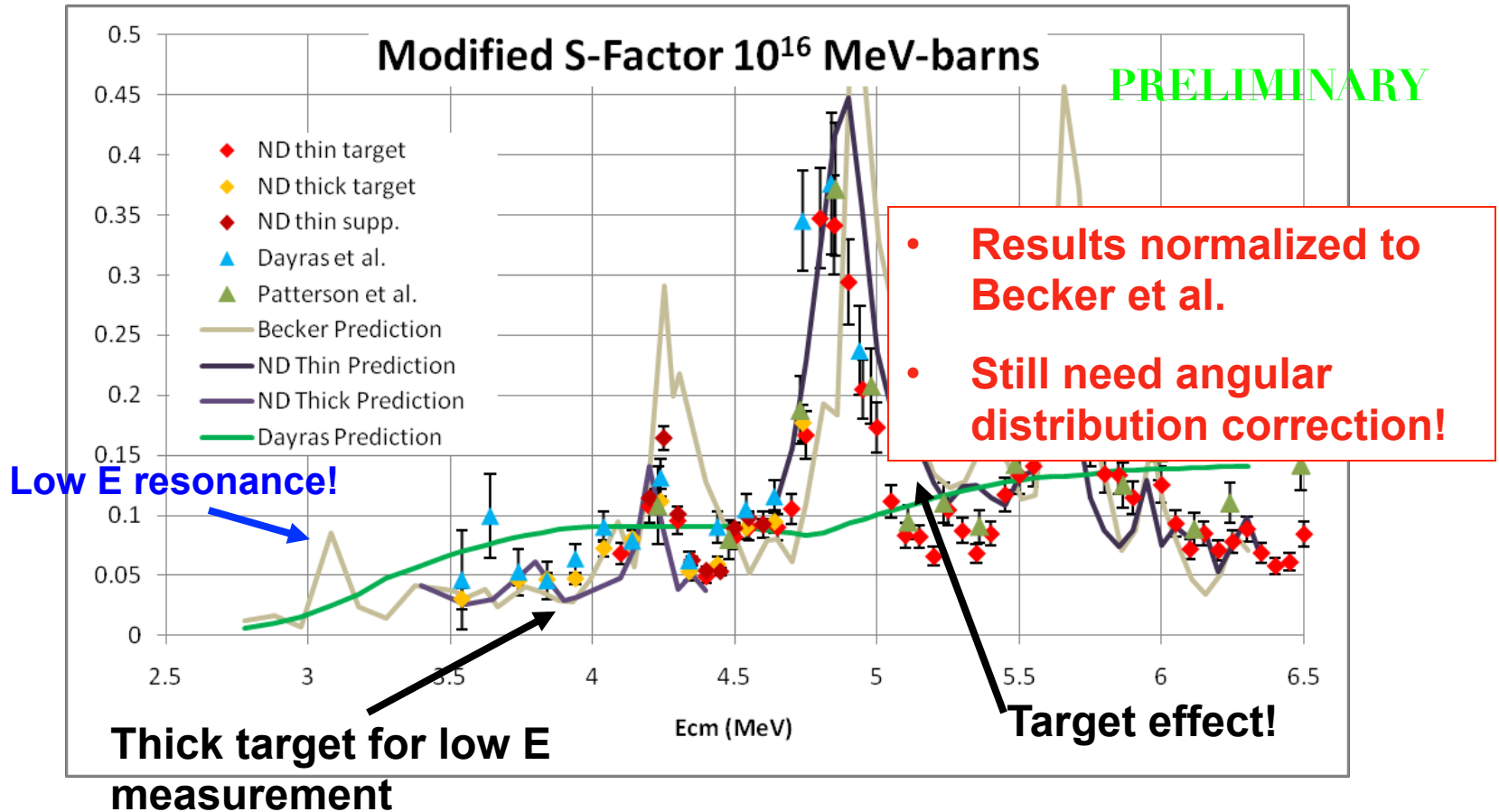


YY1 Si strip detectors



Becker et al. 1981

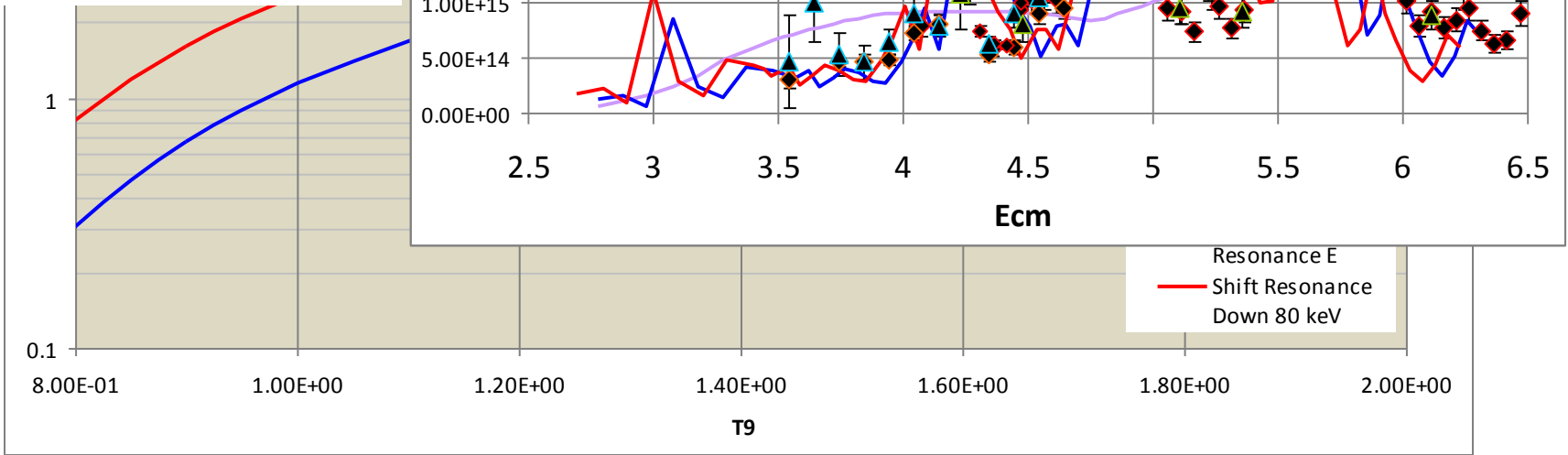
New Extrapolation



- Number of resonances reproduced, but strength & position needs improvement
- Preliminary ND results provide better match to resonance energies

Rate Calcula

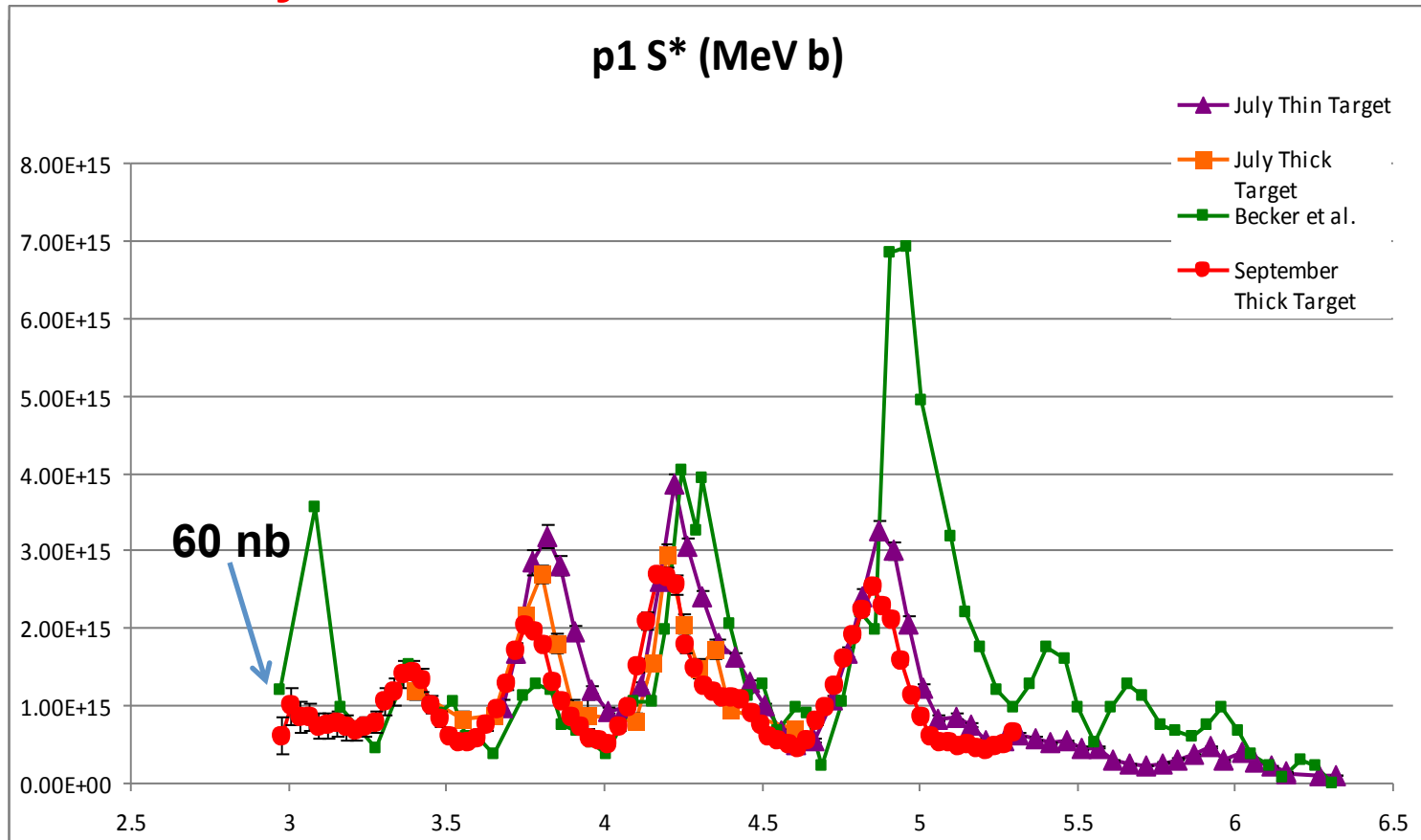
Previously we shifted Becker et al. results to match neutron data.....



Rate sensitive to resonance energy.

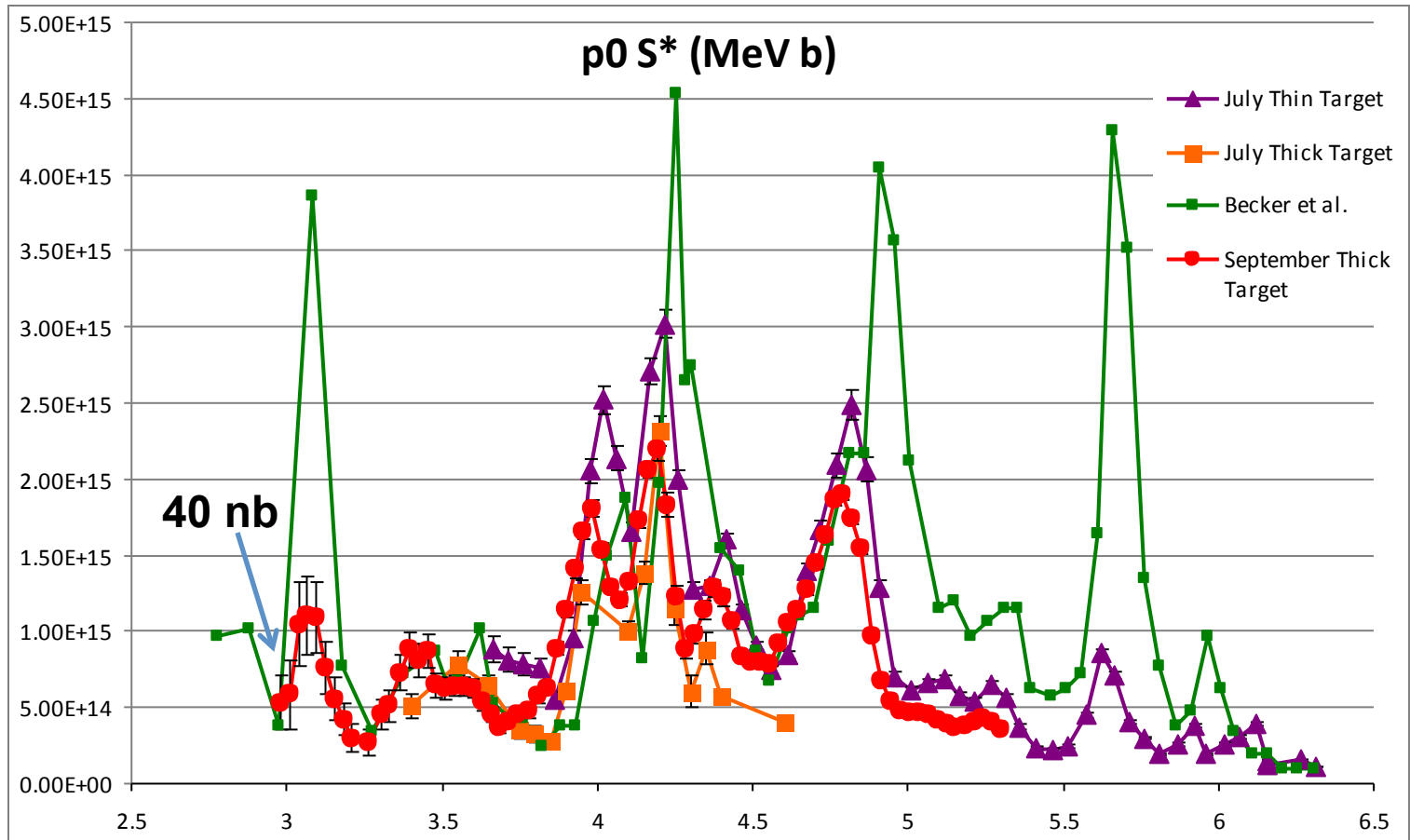
Most recent results (a few days ago) indicate there is no 3.1 MeV resonance in p1 channel ! Need more work on normalization and energy correction.

Preliminary



But the results do indicate the existence of the 3.1 MeV resonance in p0 channel!

Preliminary

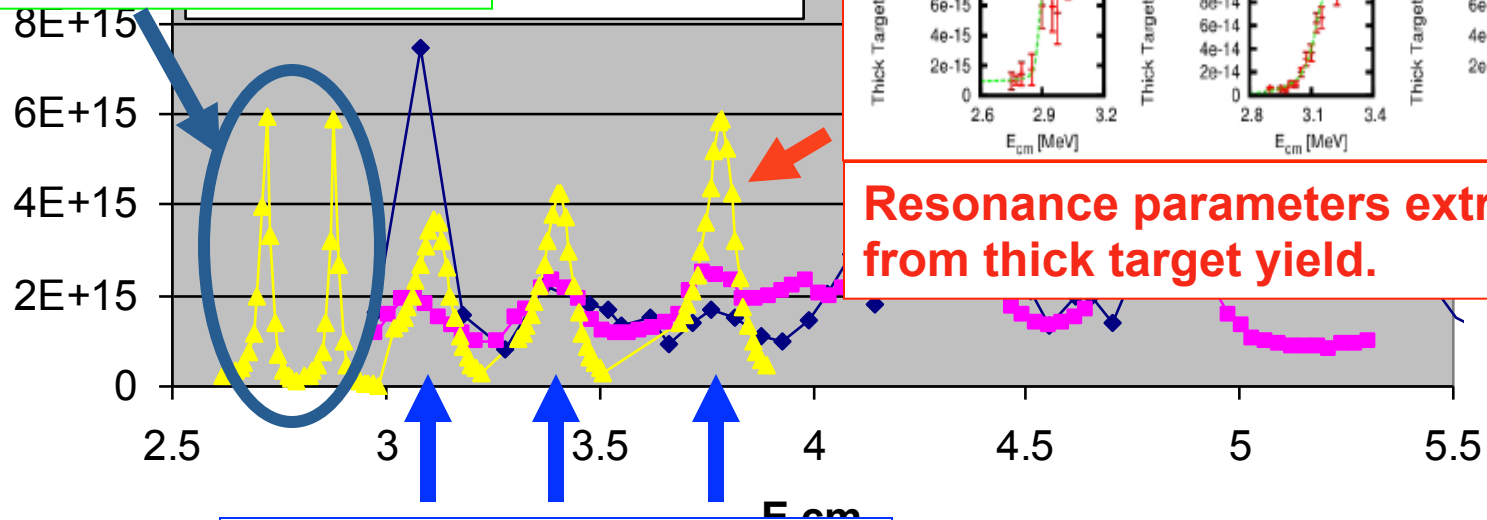


More resonances....

1. Do lower-energy resonances exist?
2. If so, are they strong enough to have an impact?

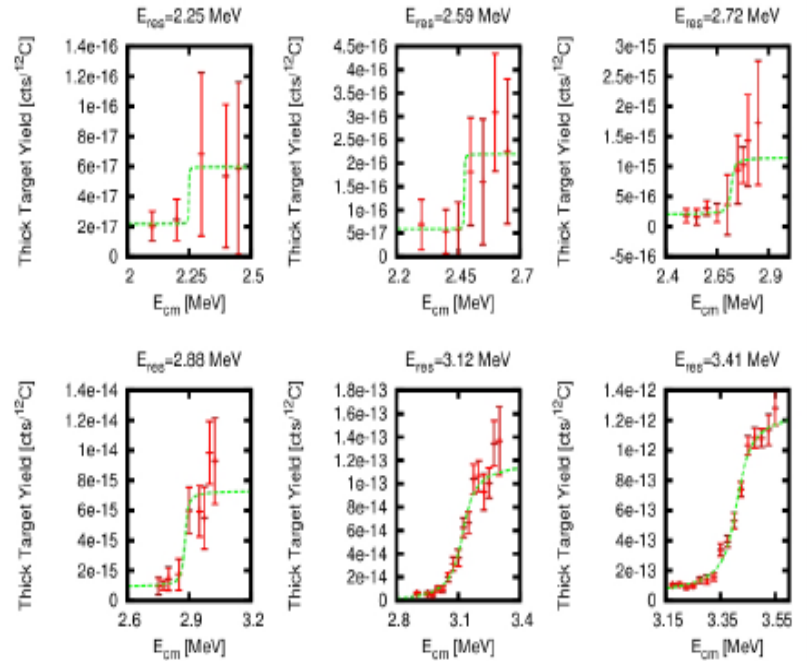
p0+p1 S* (MeV)

PhD Thesis (2010)



Resonance energies match well, but strengths differ.

Resonance parameters extracted from thick target yield.



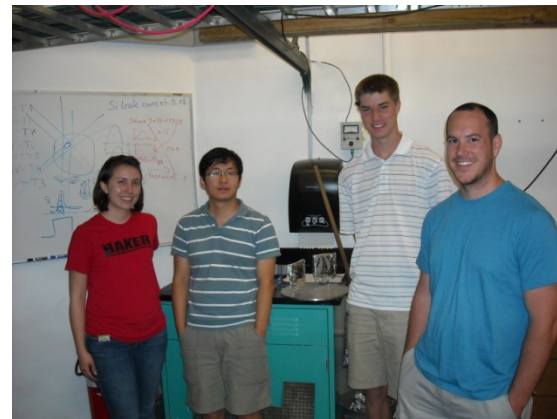
Conclusions

- Resonant structure of $^{12}\text{C}+^{12}\text{C}$ likely plays a role in astrophysical reaction rates making reliable extrapolations difficult
- Direct measurements are hindered by low x.s. and high background
- Isospin symmetry can be used to predict resonant structure in $^{12}\text{C}(^{12}\text{C},n)$
- Preliminary results indicate low-energy resonance(s) may marginally enhance rate, but more analysis and experiment(s) are still needed

Thank You!

Collaborators: X.D. Tang, X. Fang, J. Browne, A. Alongi, C. Cahillane,
E. Dahlstrom, A. Moncion, W. Tan, M. Notani

Nuclear Science Lab: S. Almaraz-Calderon, A. Ayangeakaa, A. Best, M. Couder,
J. DeBoer, W. Lu, D. Patel, N. Paul, A. Roberts, R. Talwar, A. Kontos,
M. Smith, S. Lyons



But Wait!

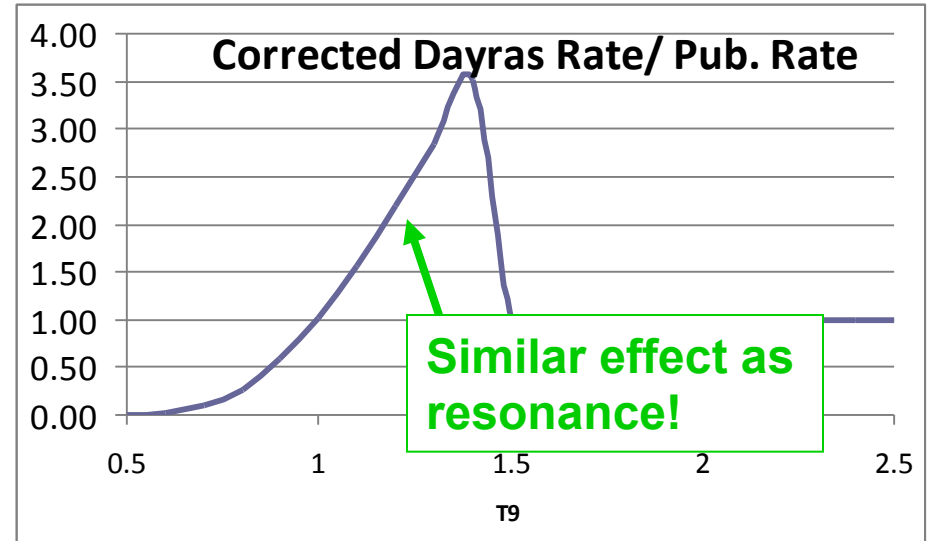
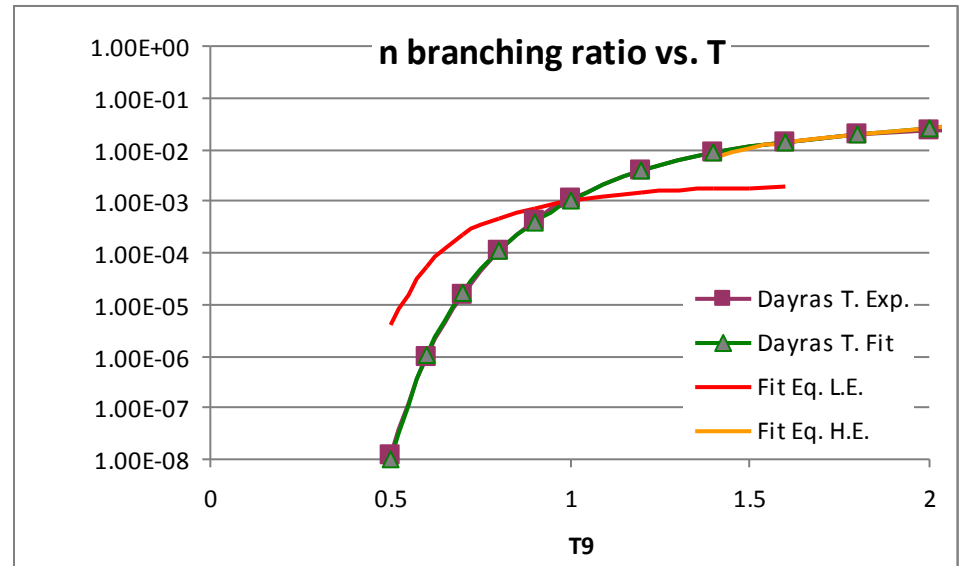
- Funny Behavior @ $T_9 = 1.5$
- Dayras low T parameters wrong
- Must re-fit data to get correct parameters

$$B_n(T_9) = \frac{\int_{E_t}^{\infty} \beta_n(E) S(E) \exp\{-[(E_G/E)^{\dagger} + E/kT]\} dE}{\int_0^{\infty} S(E) \exp\{-[(E_G/E)^{\dagger} + E/kT]\} dE},$$

TABLE 4

Neutron branching ratio as a function of temperature

T_9	E_0 (MeV)	Δ (MeV)	$B_n(T_9)$		
			this exp	fit	old
0.5	1.49	0.58	1.15(-08)	1.04(-8)	2.67(-9)
0.6	1.68	0.67	9.42(-7)	1.07(-6)	3.03(-6)
0.7	1.85	0.75	1.57(-5)	1.71(-5)	1.22(-4)
0.8	2.01	0.84	1.05(-4)	1.06(-4)	9.47(-4)
0.9	2.17	0.92	4.03(-4)	3.84(-4)	3.11(-3)
1.0	2.32	1.00	1.08(-3)	1.00(-3)	6.25(-3)
1.2	2.59	1.15	4.01(-3)	3.78(-3)	1.24(-2)
1.4	2.85	1.30	8.76(-3)	9.12(-3)	1.61(-2)
1.6	3.09	1.43	1.42(-2)	1.37(-2)	1.80(-2)
1.8	3.32	1.57	1.94(-2)	1.97(-2)	1.89(-2)
2.0	3.53	1.69	2.42(-2)	2.49(-2)	1.94(-2)
2.2	3.73	1.81	2.86(-2)	2.93(-2)	1.96(-2)
2.6	4.11	2.04	3.63(-2)	3.62(-2)	1.98(-2)
3.0	4.45	2.26	4.23(-2)	4.13(-2)	1.99(-2)
3.5	4.84	2.51	4.74(-2)	4.58(-2)	2.00(-2)
4.0	5.20	2.75	5.06(-2)	4.88(-2)	2.00(-2)
4.5	5.53	2.96	5.25(-2)	5.08(-2)	2.00(-2)
5.0	5.83	3.17	5.37(-2)	5.22(-2)	2.00(-2)



$$B_n(T_9) = 0.859 \exp\{-[(0.766/T_9^3)(1 + 0.0789T_9 + 7.74T_9^3)]\}, \quad 0.5 \leq T_9 \leq 1.5, \quad 8a)$$

$$B_n(T_9) = 0.055[1 - \exp\{-(0.789T_9 - 0.976)\}], \quad 1.5 \leq T_9 \leq 5.0. \quad (8b)$$

Dayras et al. 1977