Nuclear data needs for p-B11 fusion fuel

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on behalf of the TAE team

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Objective and summary

Improve understanding and perception of p-B11 fusion by using the highest quality nuclear data possible.

- How to get new p-B11 XS into databases - EXFOR, END/F, or FENDL?

Much like the broader fusion community, we need accurate and precise data

- Reactivity rates (primary and secondary reactants)
- Secondary particle distributions
- Minimize radionuclide inventory
- Understand radiation damage (electronic, magnetic, dielectrics, structural, etc.)

Funding pathways…

- Nuclear data evaluation is not well defined under INFUSE or ARPA-E
- Other programs?

Nuclear data improvements desired for p-B11 fuel

- Formal evaluation and acceptance of the $B11(p,\alpha\alpha)\alpha$ cross-section using recently measured data
  - New data, that is not in EXFOR, shows an increase in reactivity
- Data improvements for p-B11 at low energies < 200keV
- Double differential cross-sections for reactant products from primary, secondary and contamination reactions
  - [1)]Tri-alpha reaction originally observed by M. L. E. Oliphant and Lord Rutherford in 1933.
  - New data shows energy is carried, primarily, by two of the three alpha particles
- Spin polarization dependency in cross-sections
  - Aligning the spin of the reactants increases the cross-section by ~50-60%
  - Alpha particles preferentially born perpendicular to machine axis reduces secondary reactions.
- Be7 production via $B10(p,\alpha)Be7$ reaction
  - Understanding the need to enrich B11 and to what level to avoid beryllium contamination

1) M. L. E. Oliphant and Lord Rutherford , “Experiments on the Transmutation of Elements by Protons,” , Proceedings of the Royal Society of London Series A Vol 141, No 843 (1933)

EXFOR does not include the latest measurements which could improve the perception and viability of p-B11 fusion.

- The total cross-section is the summation of three dominant channels
  - $B11(p,\alpha^1)Be8^* \rightarrow 2\alpha$
  - $B11(p,\alpha^0)Be8 \rightarrow 2\alpha$
  - $B11(p,\alpha\alpha)\alpha$

- Sikora and Weller showed good agreement between measured and simulated alpha energy spectrum.
- Improved accounting of alpha particles at lower energies led to an increase in the inferred cross-section

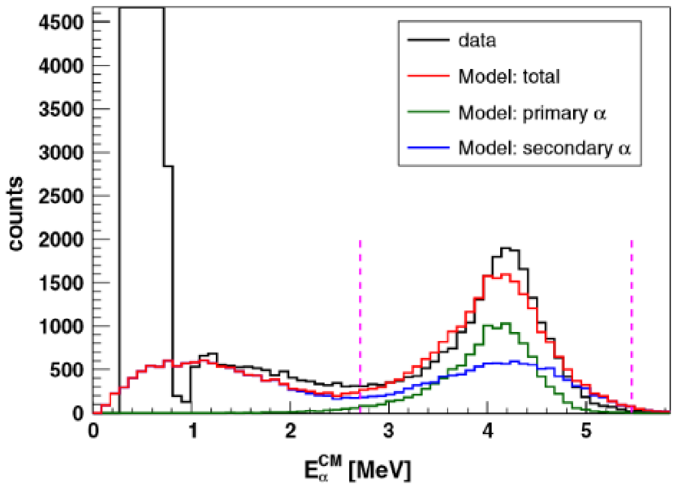
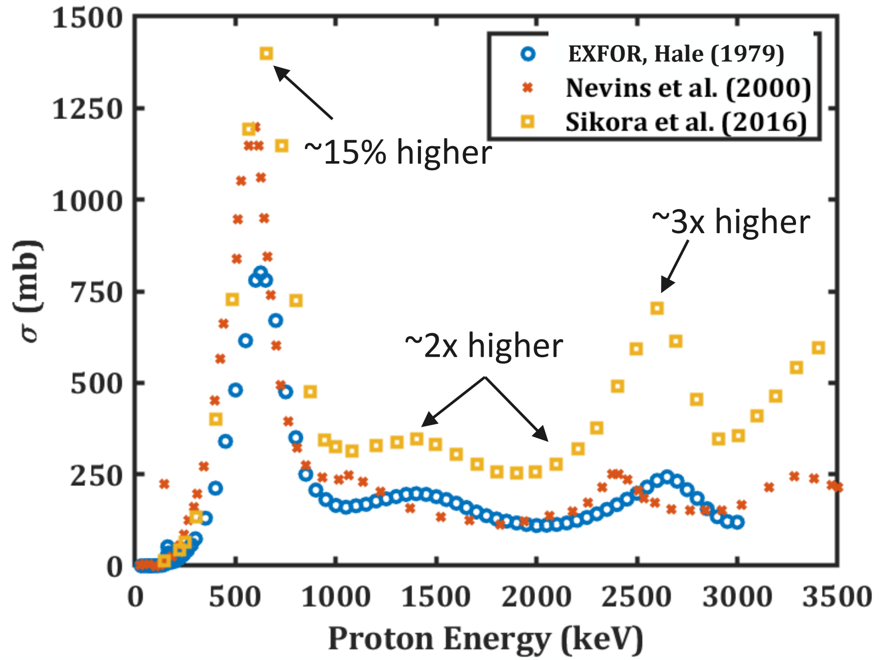


Image taken from Sikora, M. H., and H. R. Weller. Data shown at 90º and E_p = 650keV

Newer measurements and analytical approximations show a significant increase to the $\boldsymbol{B11(p,\alpha\alpha)\alpha}$ cross-section

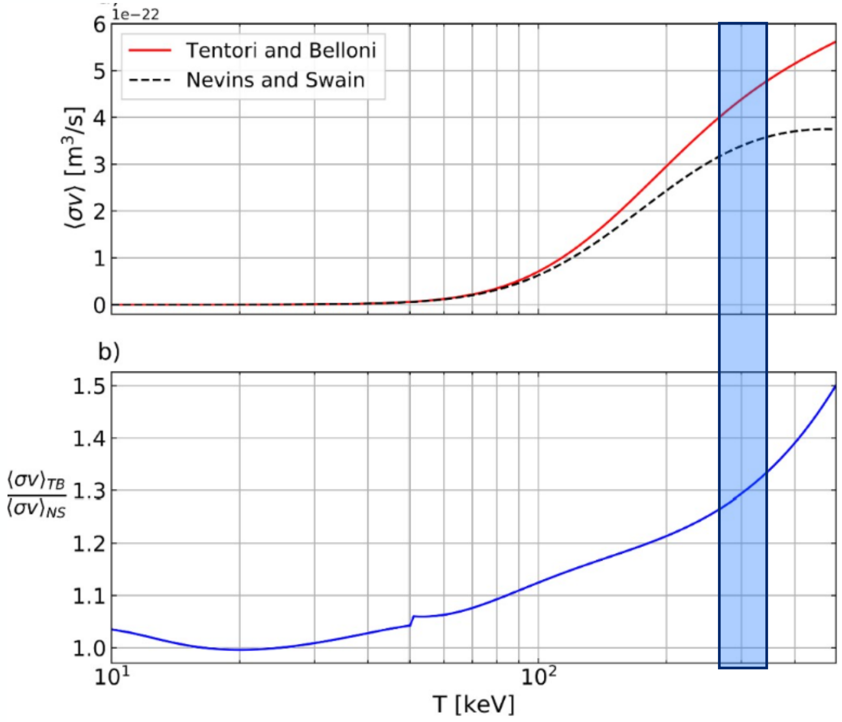


1) Data from EXFOR, Rept: Los Alamos Scientific Lab. Reports, No.7066-PR, p.2 (1977), USA
2) W. M. Nevins and R. Swain, "The thermonuclear fusion rate coefficient for p-B^11reactions", Nucl. Fusion 40, 865 (2002)
3) Sikora, M. H., and H. R. Weller. "A new evaluation of the 11 B (p, α) α α reaction rates." *Journal of Fusion Energy* 35.3 (2016): 538-543.

“Ignition” conditions are possible with a higher reactivity.

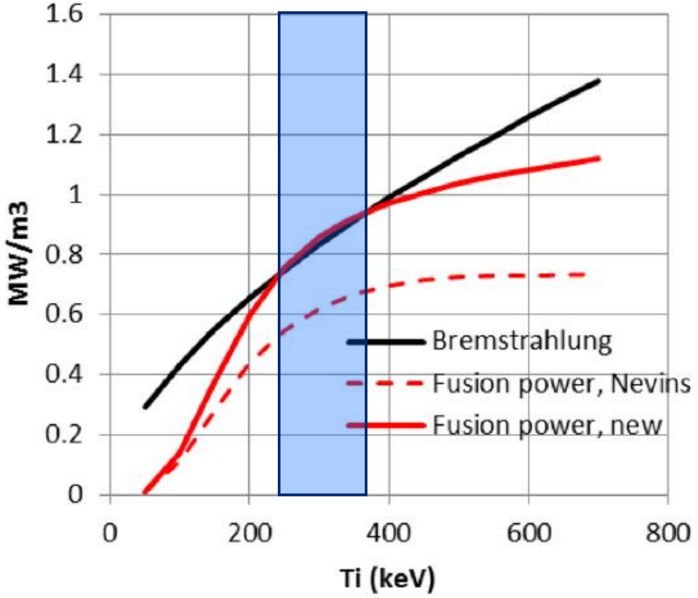
[1])Recently, Tentori et al. proposed new cross-sections based on the work of Sikora and Weller

- 30% higher reactivity at 300keV, 50% higher at 500keV when compared to Nevins and Swain



Higher reactivity shows ignition relevant conditions are obtainable

[2])A simple power balance shows fusion power exceeds bremsstrahlung losses for ion-temperatures between 250 and 350keV



1) Alessandro Tentori and Fabio Belloni, “Revisiting p-11B fusion cross section and reactivity, and their analytical approximations,” Nucl. Fusion 63 (2023).

2) S. V. Putvinski et al., “Fusion reactivity of the pB11 plasma revisited,” Nucl. Fusion 59 (2019).

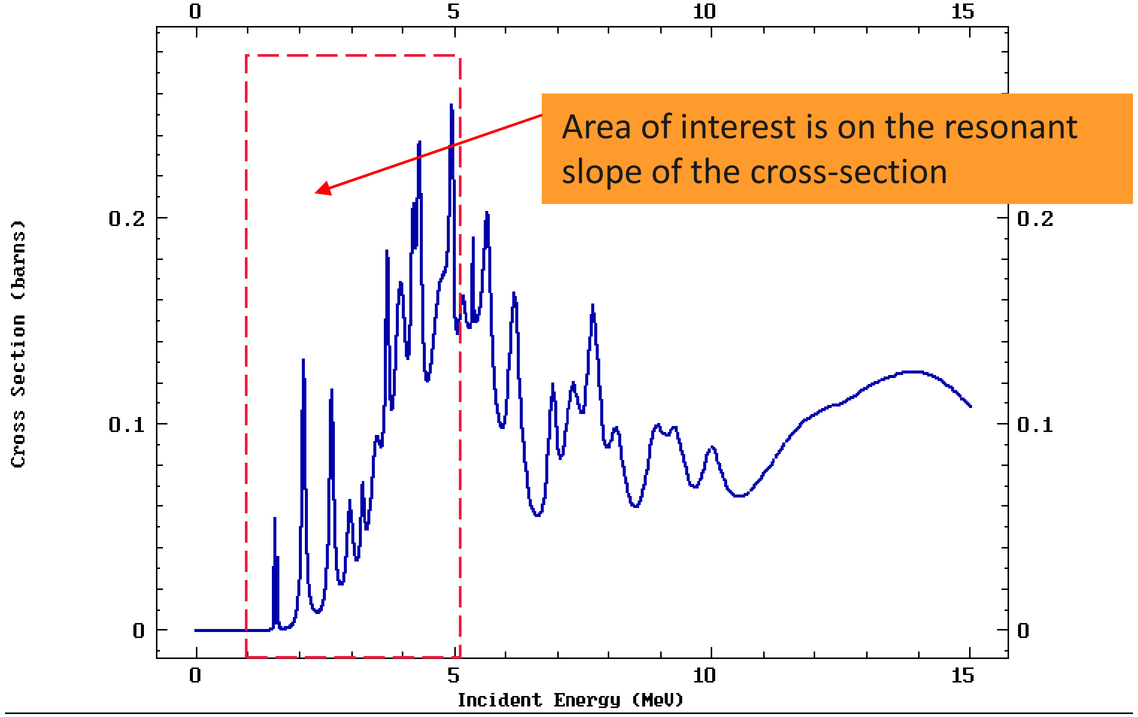
Current state of nuclear data for reactions relevant to p-B11 fuel

	1. Primary Reactions	
EXFOR	$^{11}B(p,\alpha\alpha)\ \alpha$	Q= 8.682 MeV
EXFOR	$^{11}B(p,\gamma)\ ^{12}C$	Q=15.957 MeV
	2. Secondary Reactions	
JENDL-5	$^{11}B(\alpha,n)\ ^{14}N$	Q=0.158 MeV
JENDL-5	$^{11}B(\alpha,p)\ ^{14}C$	Q=0.784 MeV, $T_{1/2}(^{14}C)$=5700 yrs
	3. Primary Contamination Reactions	
ENDF-VIII	$^{10}B(p,\alpha)\ ^{7}Be(\beta^+)\ ^{7}Li$	Q_{Be}=1.145 MeV, $T_{1/2}(^{7}Be)$=53.22 days; Q_{Li}=0.862 MeV
EXFOR	$^{10}B(p,\gamma)\ ^{11}C(\beta^+)\ ^{11}B$	Q=8.689 MeV, $T_{1/2}(^{11}C)$=20.3 min
FENDL 3.1C	$^{11}B(d,n)\ ^{12}C$	Q=13.732 MeV
FENDL 3.1C	$^{11}B(d,2n)\ ^{11}C(\beta^+)\ ^{11}B$	Q= - 4.989 MeV
FENDL 3.1C	$^{10}B(d,n)\ ^{11}C(\beta^+)\ ^{11}B$	Q_C=6.465 MeV, Q_B=1.982 MeV
	4. Secondary Contamination Reactions	
ENDF-VIII	$^{10}B(\alpha,n)\ ^{13}N$	Q=1.058 MeV
EXFOR	$^{10}B(\alpha,p\gamma)\ ^{13}C$	Q=4.062 MeV

Slide courtesy of Henk M.

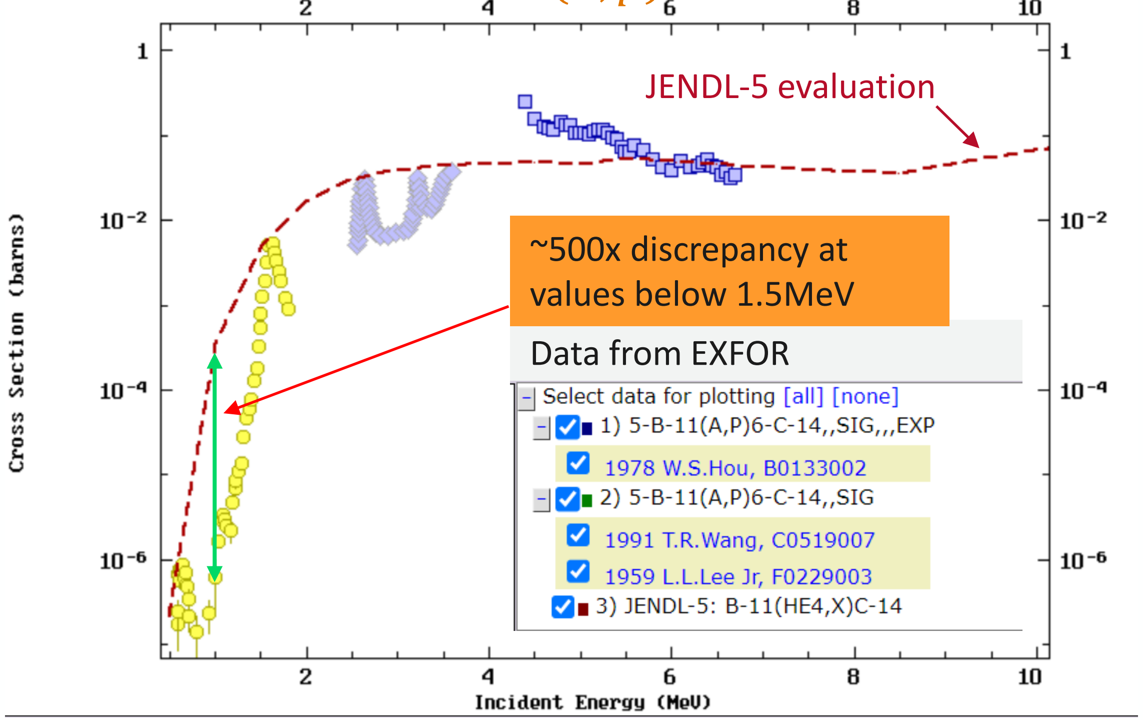
Understanding the alpha particle distribution is a high priority for radiation safety and nuclide inventory.

$B11(\alpha, n)$N14 (JENDL-5 Database)



Primary source of neutrons which will impact facility design and radiation safety

$B11(\alpha, p)C14$



Source of long-lived C14 in the fuel

- Large data gaps around 2 and 4 MeV
- Order-of-magnitude variations between measured and evaluated data

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Thank You

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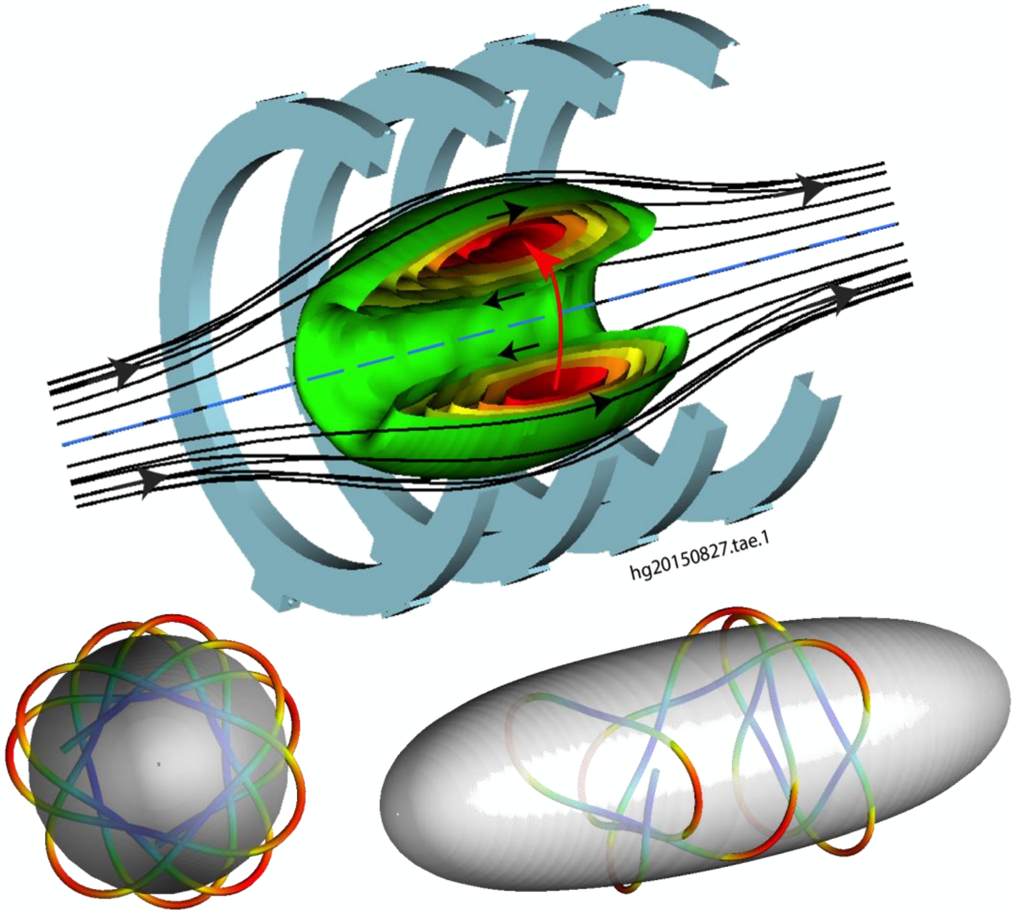
Other slides

The TAE Concept: P-B11 fuel with Beam Driven Field Reverse Configuration (FRC)



Large orbit ions via Neutral Beam injection

- Aneutronic Fuel[1] (<1% of energy in neutrons)
- High plasma β ~ 1 (plasma pressure / B^2)
  - Compact and high-power density
  - Indigenous large orbit particles
- Tangential Neutral Beam Injection
  - Large orbit ion population
  - Increased stability and reduced transport
- Significant engineering advantages that translate to viable reactor economics

1) https://www.njleg.state.nj.us/2006/Bills/A3000/2731_I1.HTM

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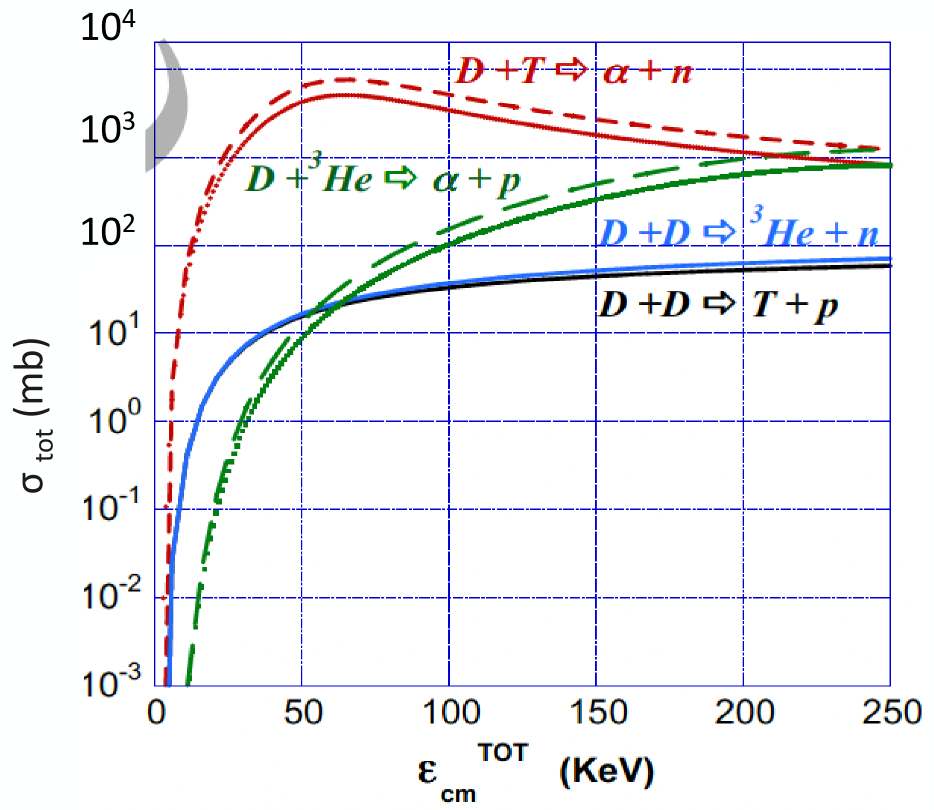
Spin-polarized Fusion

using nuclear physics to increase fusion yield

- DT and D^{3}He fusion both have spin 3/2 resonances just above the particle-decay thresholds in the compound nuclei
- Aligning the spins of the reactants in these fuels increases the fusion cross-section by ~50% [1,2,3]
- Experimental and theoretical investigations are underway to develop techniques to create and maintain polarized populations under fusion relevant conditions [4]
- It would be useful to have precise nuclear data to quantify the cross-section as a function of spin polarization for all relevant fusion fuels



[1]Kulsrud, et al. Physical Review Letters, **49** (17) 1982

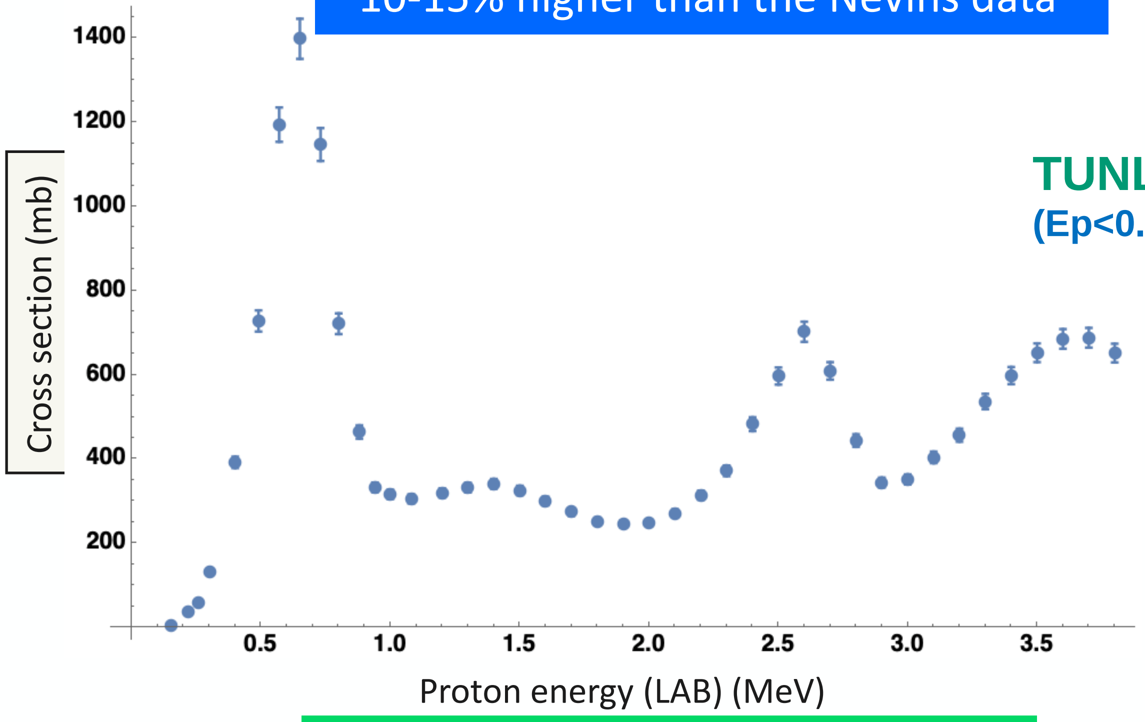
[2]Ciullo, et al. JPS Conf. Proc. **37**, 021302 (2022)

[3]Baylor, et al. Nucl. Fusion (2023), 10.1088/1741-4326/acc3ae

[4]Garcia, et al. Nucl. Fusion **63,** 026030 (2023)

Re-evaluation of recent data could improve understanding and viability of P-B11 fusion.

~10-15% higher than the Nevins data[2]

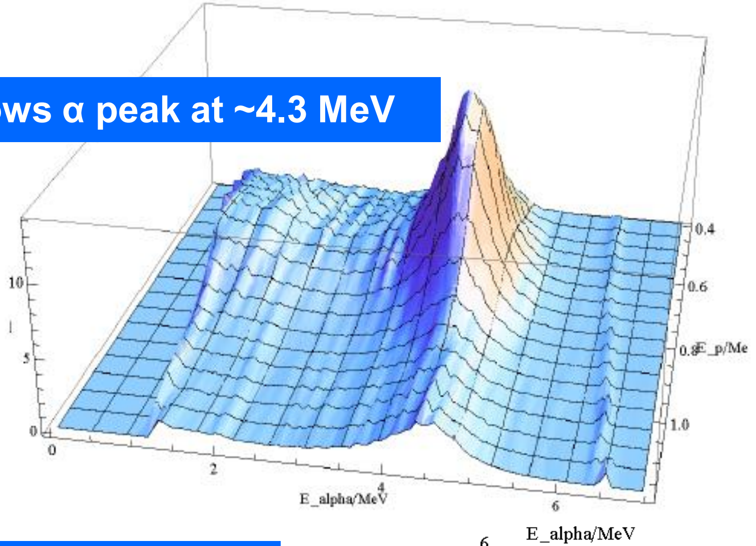


$B11(p, \alpha\alpha)\alpha$ *total cross − section*

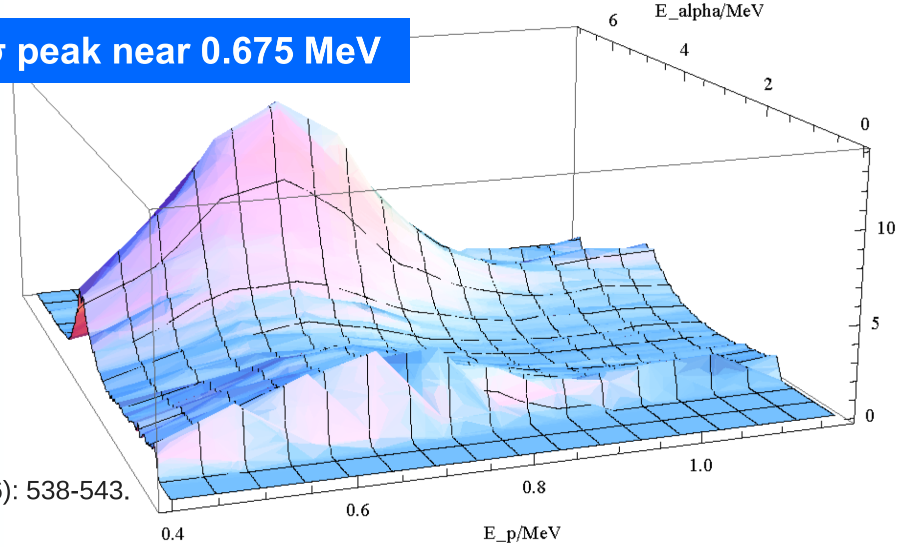
TUNL results for S(Ep,Eα)[1]

(Ep<0.4 MeV, Eα<1 MeV missing)

shows α peak at ~4.3 MeV



shows σ peak near 0.675 MeV



1) Sikora, M. H., and H. R. Weller. "A new evaluation of the 11 B (p, α) α α reaction rates." *Journal of Fusion Energy* 35.3 (2016): 538-543.
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Other cross-sections of interest