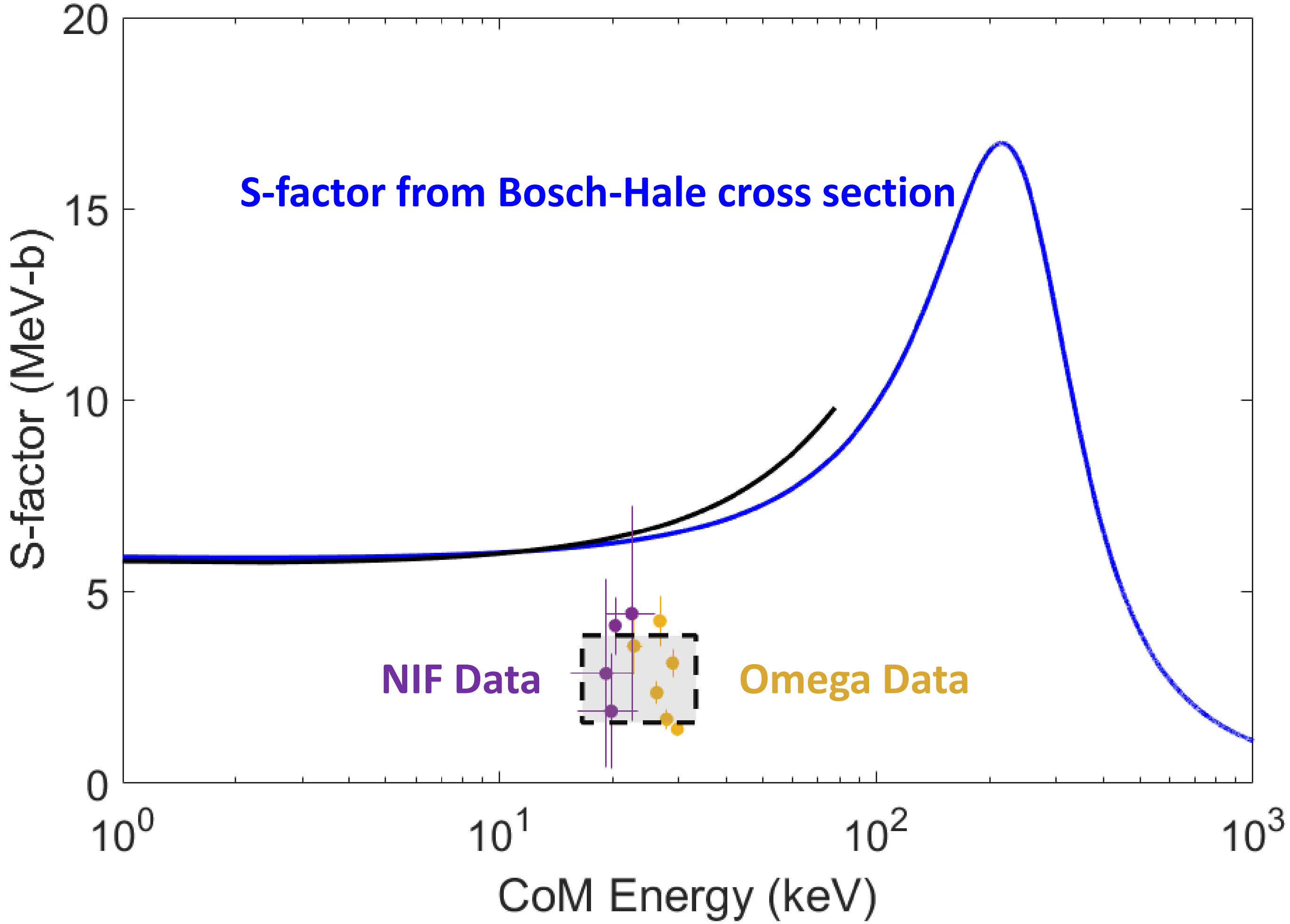
Using the PTOF and WRF diagnostics to measure the D^3He s-factor from ICF implosions



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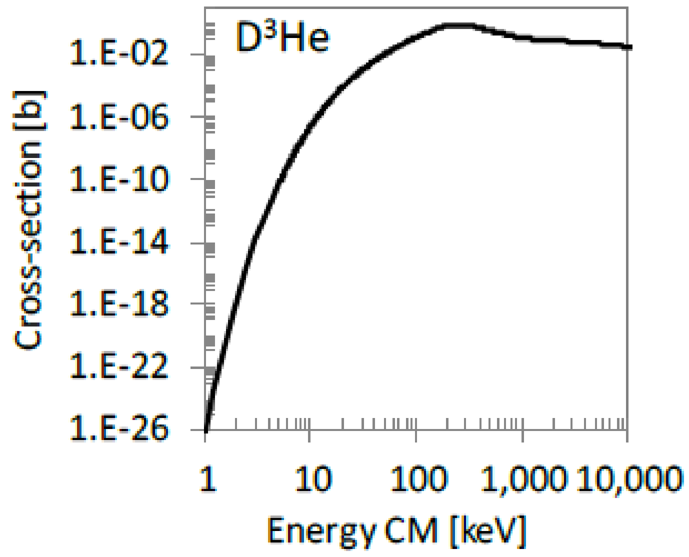
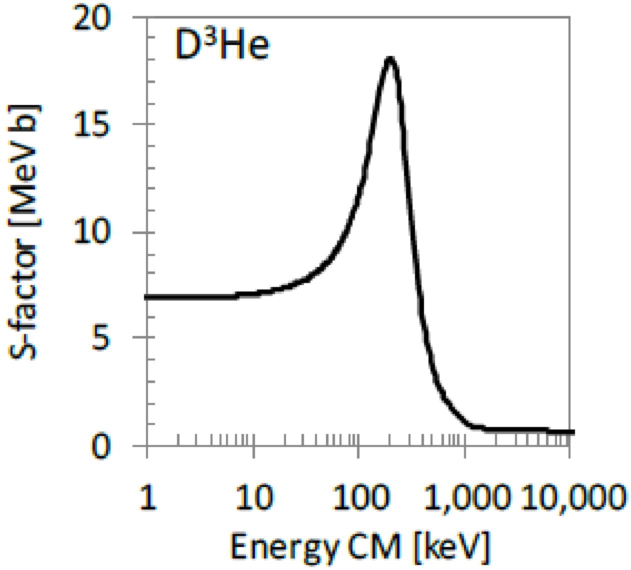
S-factor is a reparameterization of nuclear reactions cross section which removes strong dependencies on known physics

$$S(E_{CoM}) = \sigma E_{CoM} e^{\sqrt{E_G/E_{CoM}}}$$

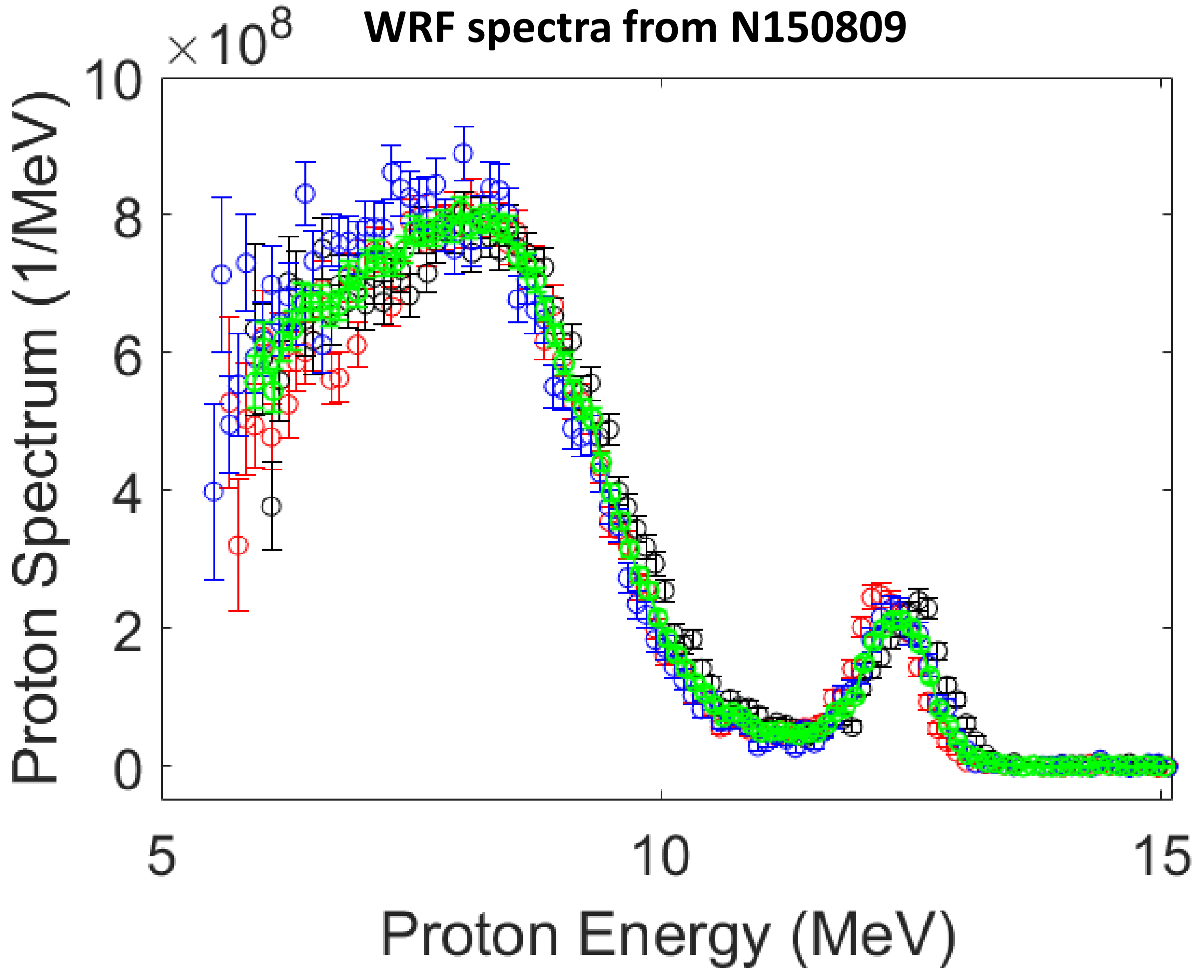
Where
E_{CoM} is the center of mass energy of the reaction
σ is the reactivity at that energy
E_G is the Gamow penetration energy of the reaction, 4.73 MeV for D^3He

This formulation removes the strong dependencies on the de Broglie wavelength (E_{CoM}), and coulomb barrier penetration ($e^{\sqrt{E_G/E_{CoM}}}$).



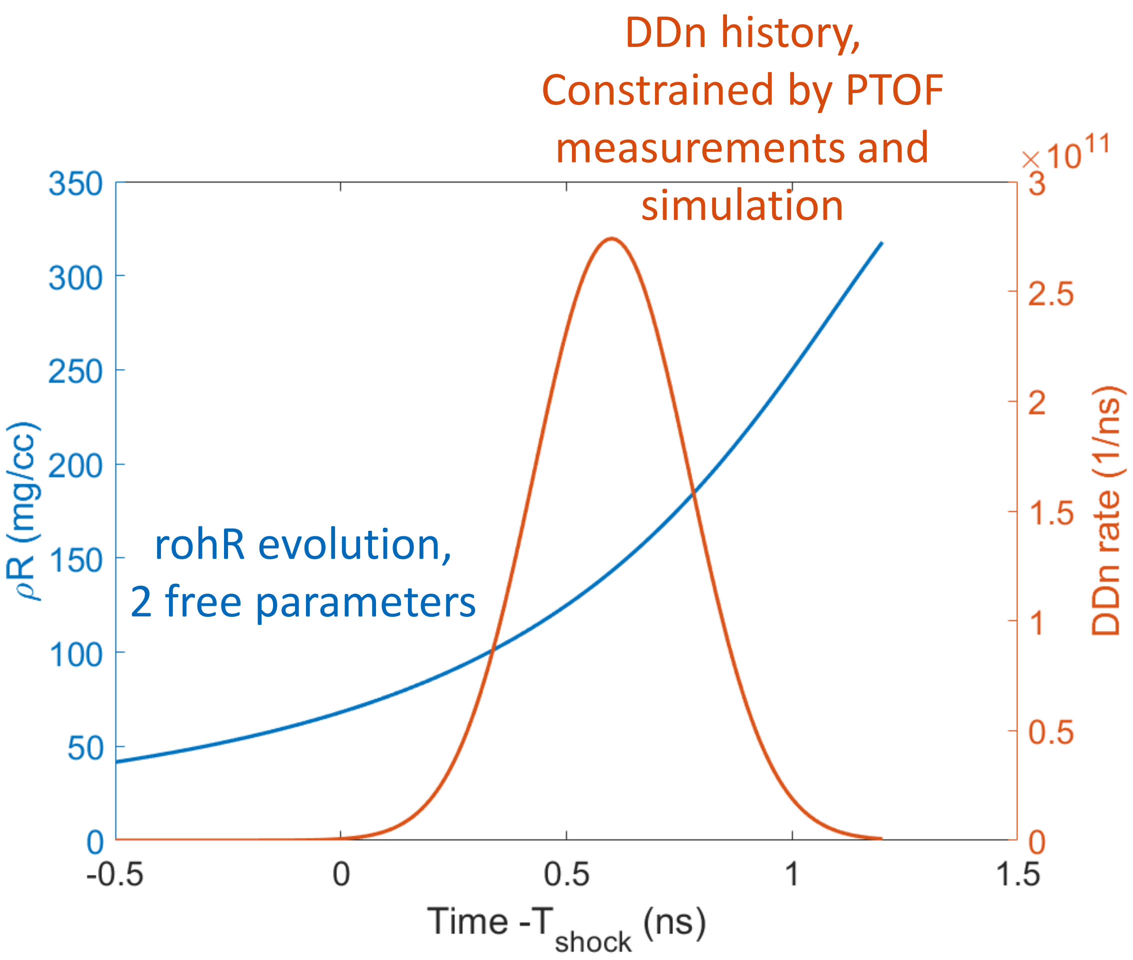


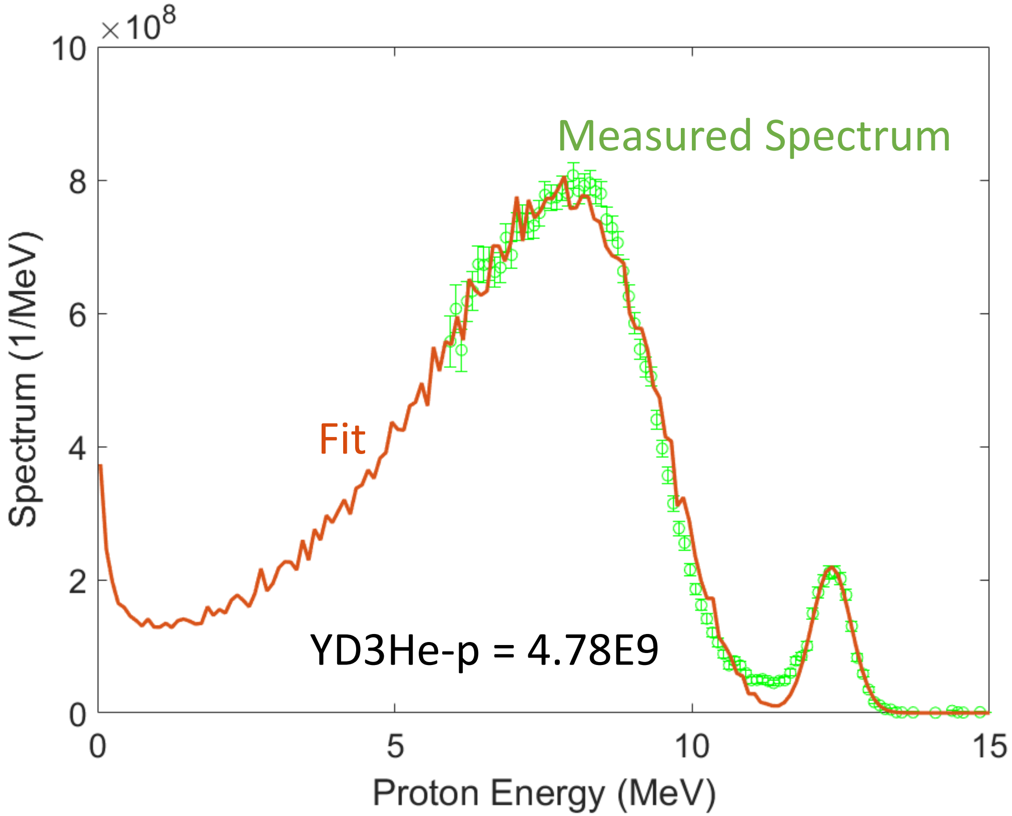
Several NIF BigFoot shots had areal densities (ρR) low enough for the WRFs to capture a large fraction of the emitted D^3He proton spectra



Wedge Range Filters (WRFs) are compact proton spectrometers that are regularly fielded on the NIF.

To infer the total proton yield from NIF implosions, the combined PTOF nuclear bang time and WRF data is fit to a ρR evolution

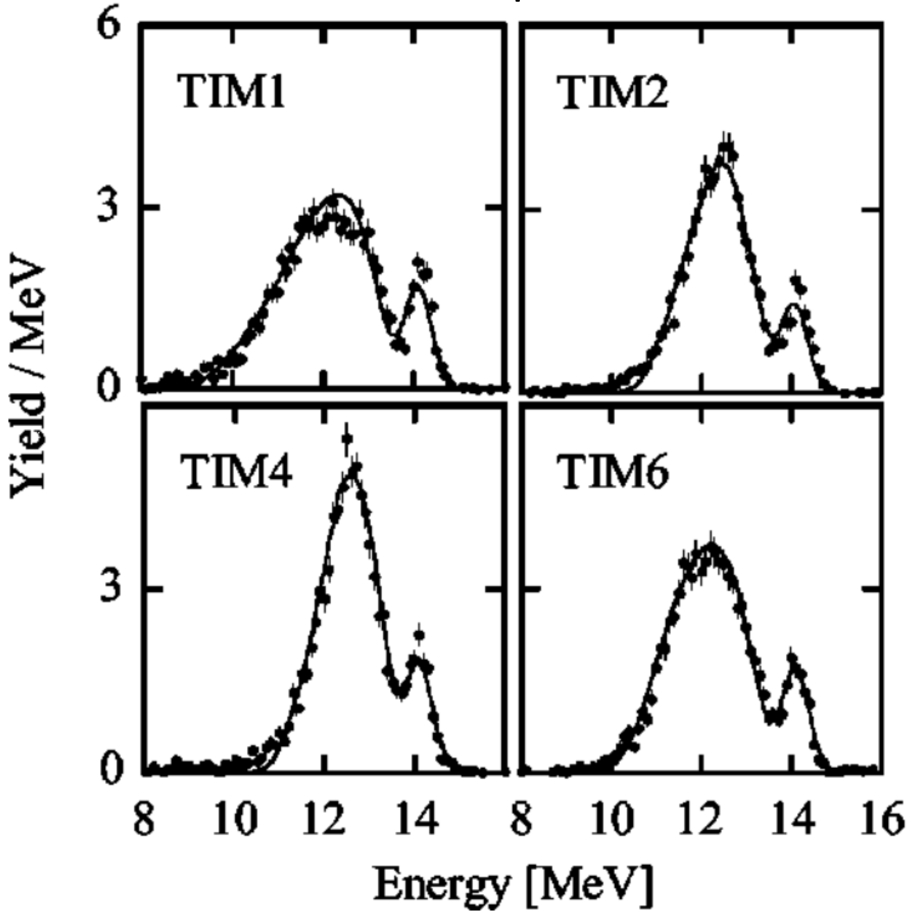




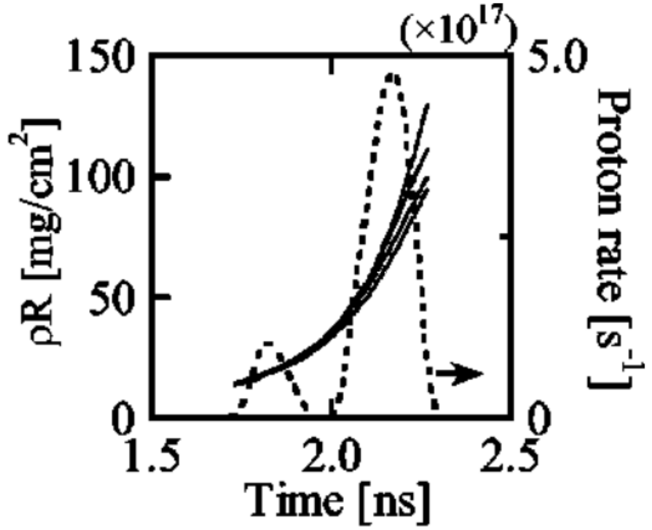
The Particle Time of Flight (PTOF) diagnostic is regularly used to measure shock and compression bang times on the NIF. See Ben Reichelt's poster in this session.

Similar data has been collected at OMEGA where the entire D3He-p spectrum is captured on the WRF

WRF spectra



Measured proton emission history, and inferred ρR evolution



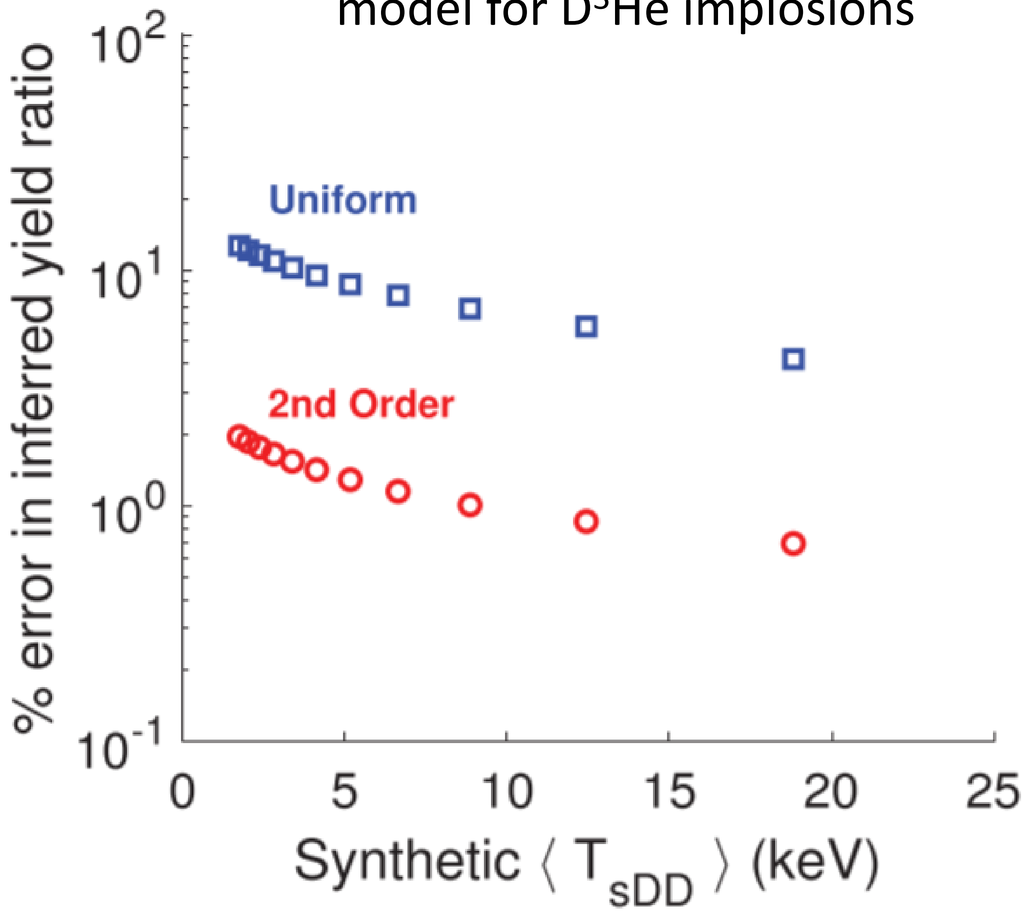
This data was originally collected to investigate ρR evolution (J. Frenje et. al. Phys. Plasmas, Vol. 11, No. 5, May 2004), but is being reused for this study.

In ICF it would be difficult to directly measure the S-factor, but a reactivity can be inferred using a uniform model with ~10% error

$$\langle \sigma v \rangle_{D3Hep} = \frac{1}{2}\frac{\boldsymbol{Y_{D3Hep}}}{\boldsymbol{Y_{DDn}}}\frac{f_D}{f_{3He}}\langle \boldsymbol{\sigma v} \rangle_{\boldsymbol{DDn}}$$

Using a uniform model the D³Hep reactivity can be estimated from the yield ratio, fill fractions (*f*), and DDn reactivity

Error when using a uniform model for D³He implosions



Kabadi et. al., Phys. Plasmas 28, 022701 (2021)

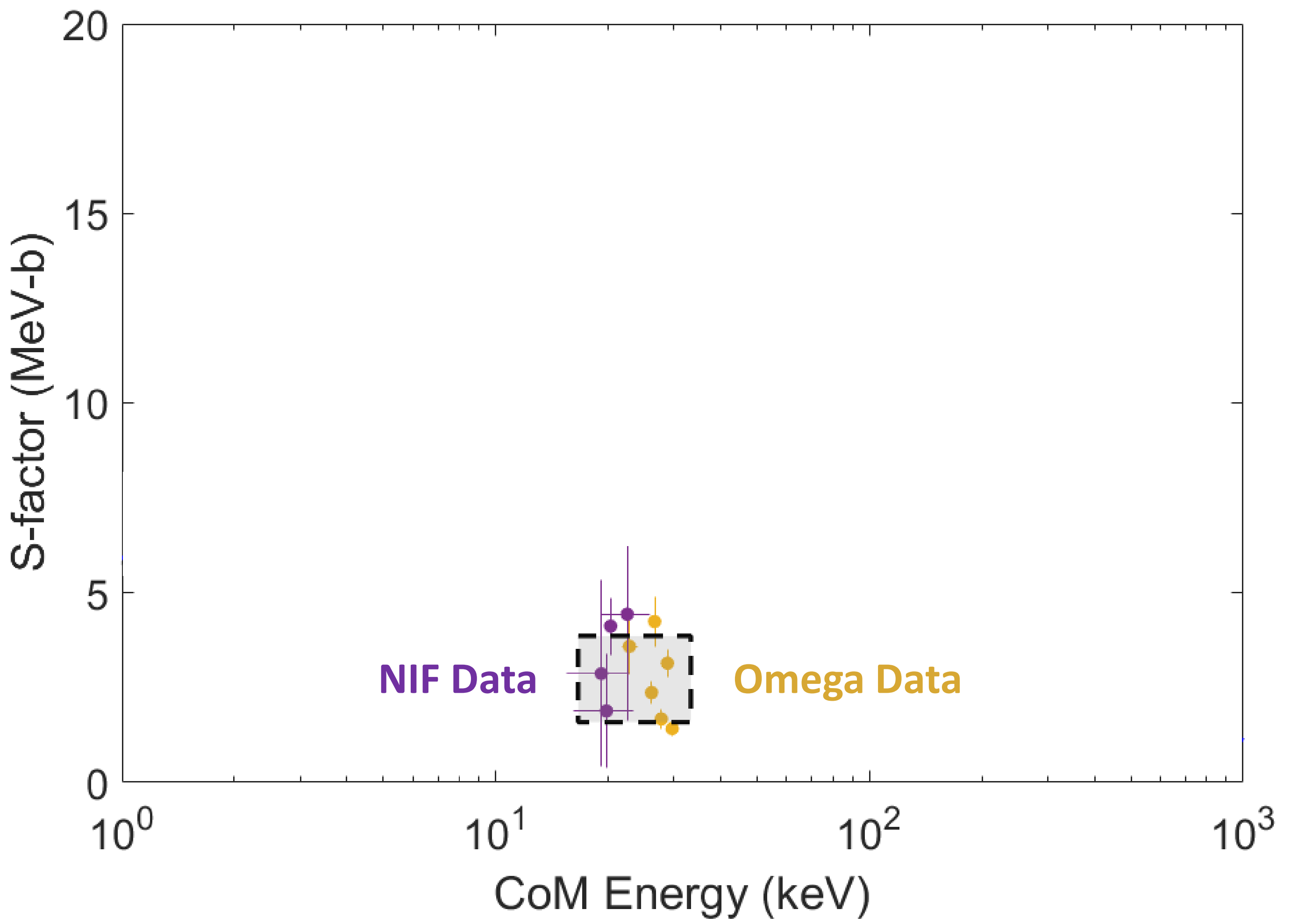
From the inferred D^3Hep reactivities and DDn ion temperatures the S-factor and effective CoM energy are estimated

$$E_{CoM} \approx \left(\frac{T}{2}\sqrt{E_G}\right)^{2/3}$$

$$E_G = 4730 \text{ keV}$$

$$\tau = \frac{3E_{CoM}}{T}$$

$$\boldsymbol{S(E_{CoM}) \approx \frac{3}{4}\sqrt{\frac{m_r T}{2\tau}} e^{\tau}\left(1 + \frac{5}{12\tau}\right)^{-1} \langle \sigma v \rangle}$$



The values inferred from NIF and OMEGA data are significantly lower than values from accelerator experiments

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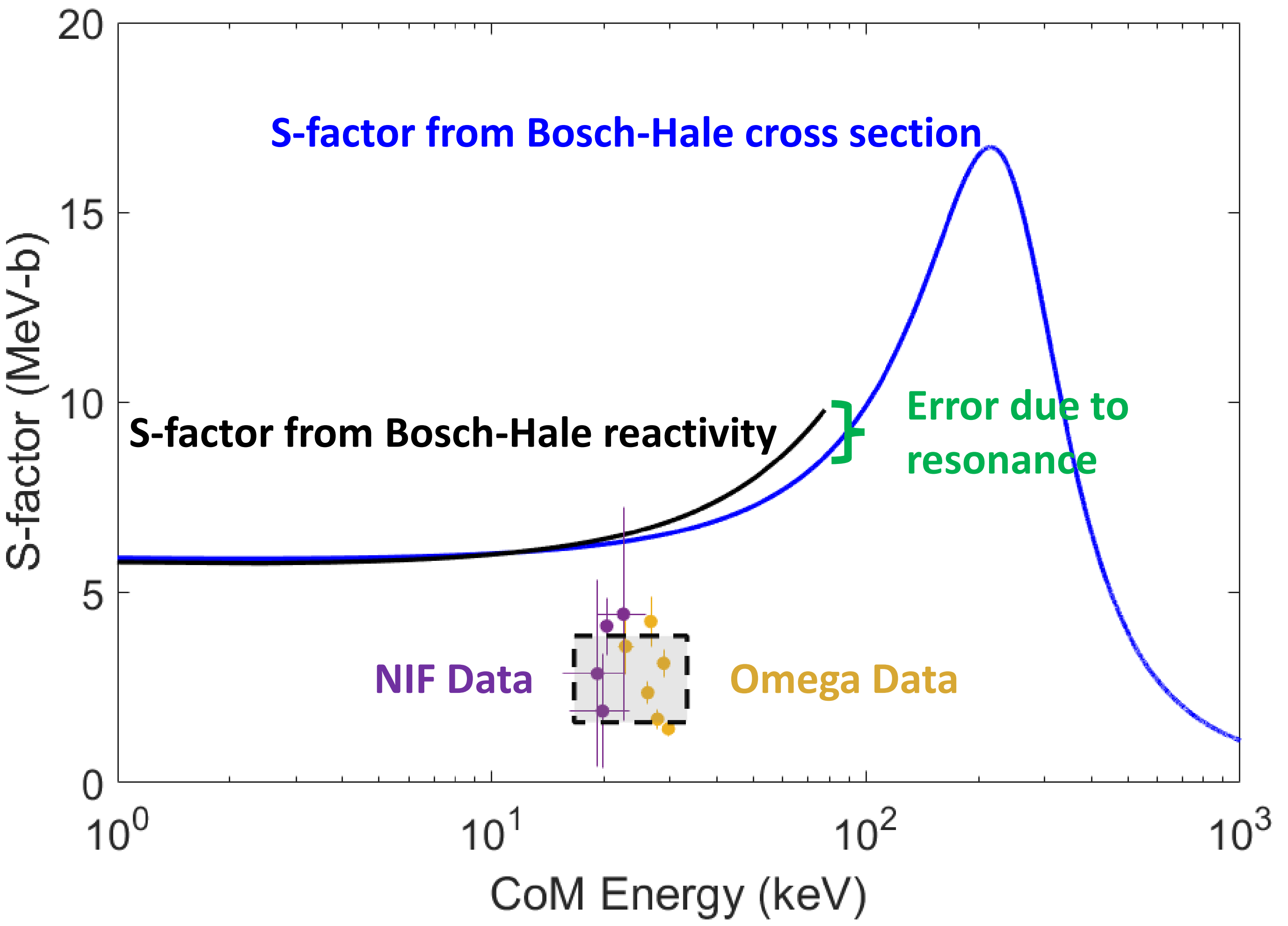


The Bosch-Hale cross section is a parameterization of an R-matrix fit to accelerator data

H.-S. Bosch and G.M. Hale 1992 *Nucl. Fusion* **32** 611

The S-factor inferred from ICF data is significantly lower than the value from accelerator measurements

- Many possible explanations for the discrepancy have been investigated and eliminated
  - The necessary flow amplitude would be too large to be physical
  - The impact of temperature profiles increases the discrepancy
  - Species separation caused by diffusion of deuterium would increase the discrepancy
  - The electron screening correction to accelerator data would need to be extremely incorrect to explain the discrepancy

- Further synthetic data studies are being done to confirm the accuracy of this result

- Any suggestions for effects to investigate would be appreciated!

Extra slides

NACREII is another comparison point which uses a direct empirical fit to accelerator experiments

NACREII is a direct empirical fit to accelerator measurements

Accelerator data from NACREII

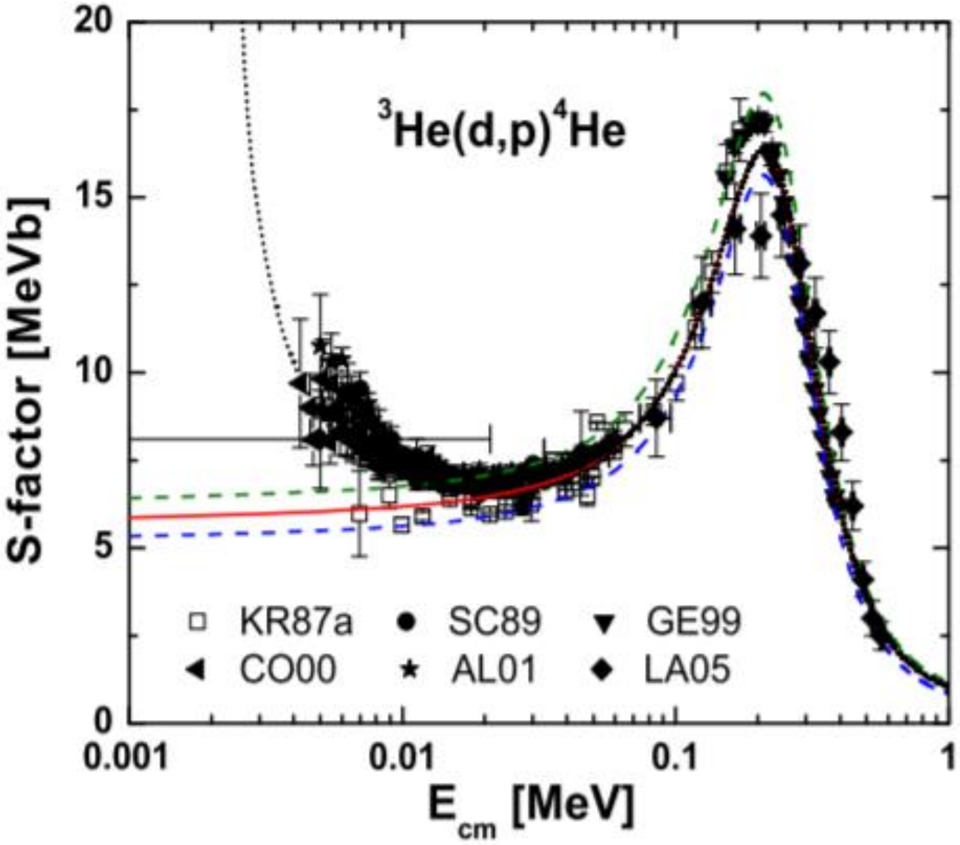


Figure 16: The S-factor for ^{3}He (d , p) ^{4}He . The dotted line indicates an adiabatic screening correction (U_e = 119 eV) to the 'adopt' curve (solid line).

Both the Bosch-Hale and NACREII fits include a large bound electron screening correction at low energy

$$\frac{S_{screened}}{S} \approx e^{\frac{1}{2}\sqrt{\frac{E_G}{E_{CoM}}}U_e \Big/ E_{CoM}}$$

$U_e \approx 0.11$ for D3He

Accelerator data from NACREII

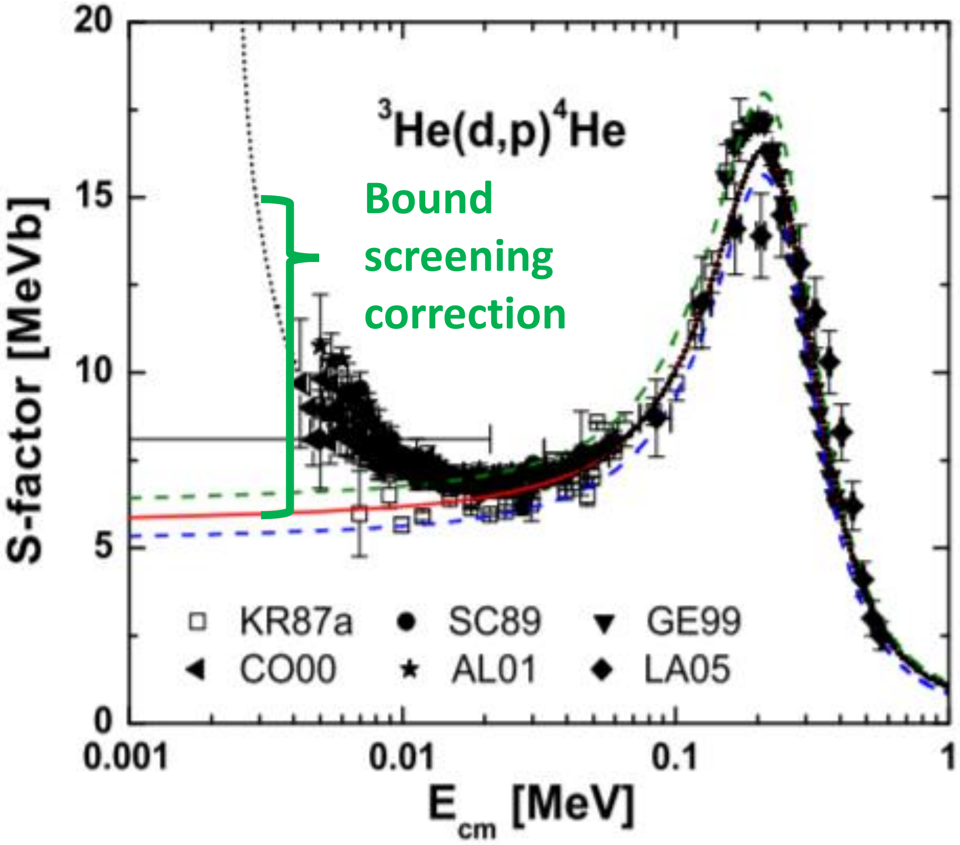
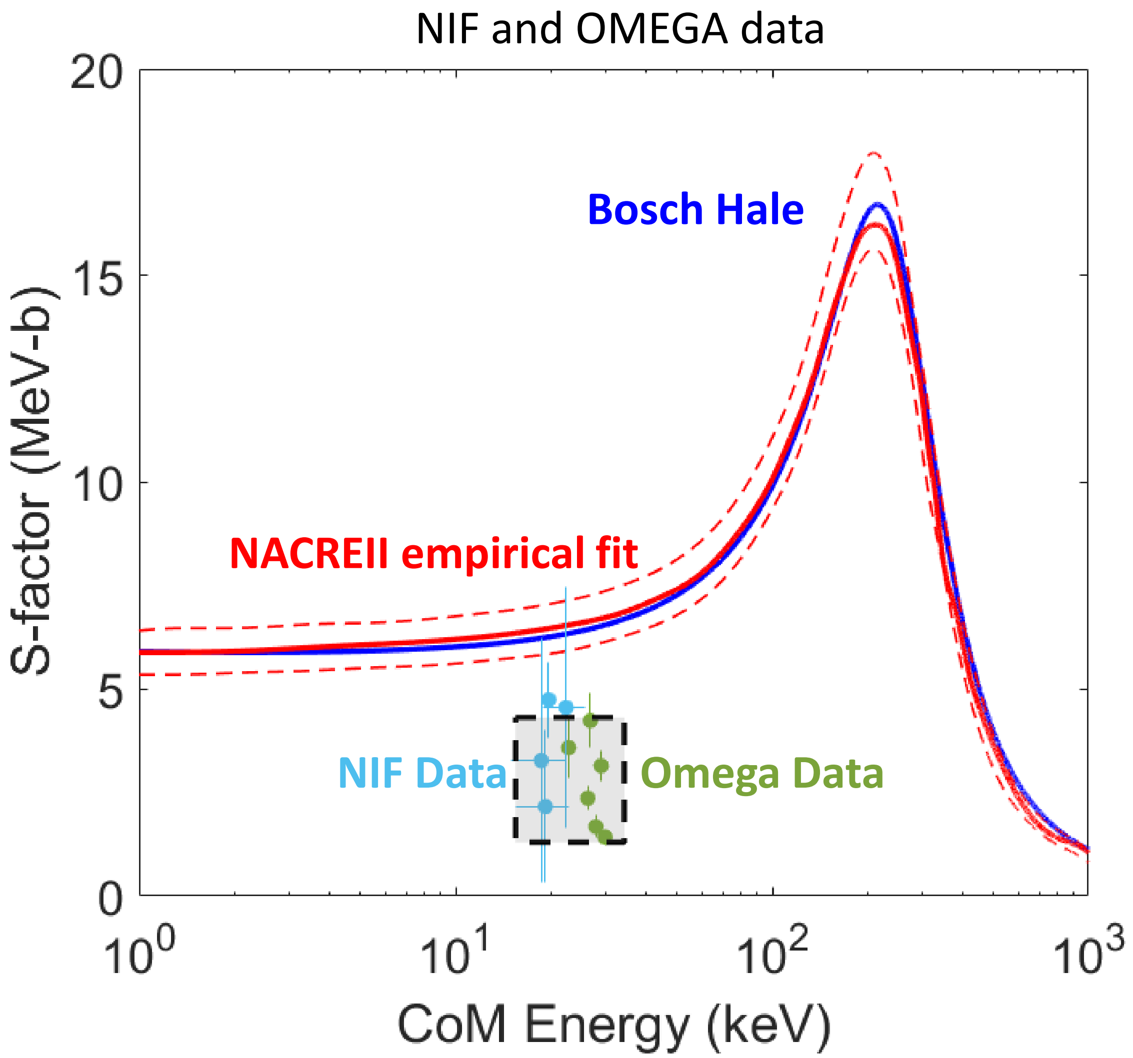


Figure 16: The S-factor for $^3He(d,p)^4He$. The dotted line indicates an adiabatic screening correction (U_e = 119 eV) to the 'adopt' curve (solid line).

Bosch-Hale and NACREII largely agree while the ICF data is significantly lower



Possible explanations

- Thermal decoupling
- Profile effects
- Species separation
- Flows
- D3He-p yield measurement is wrong
- Fits to the accelerator data are wrong

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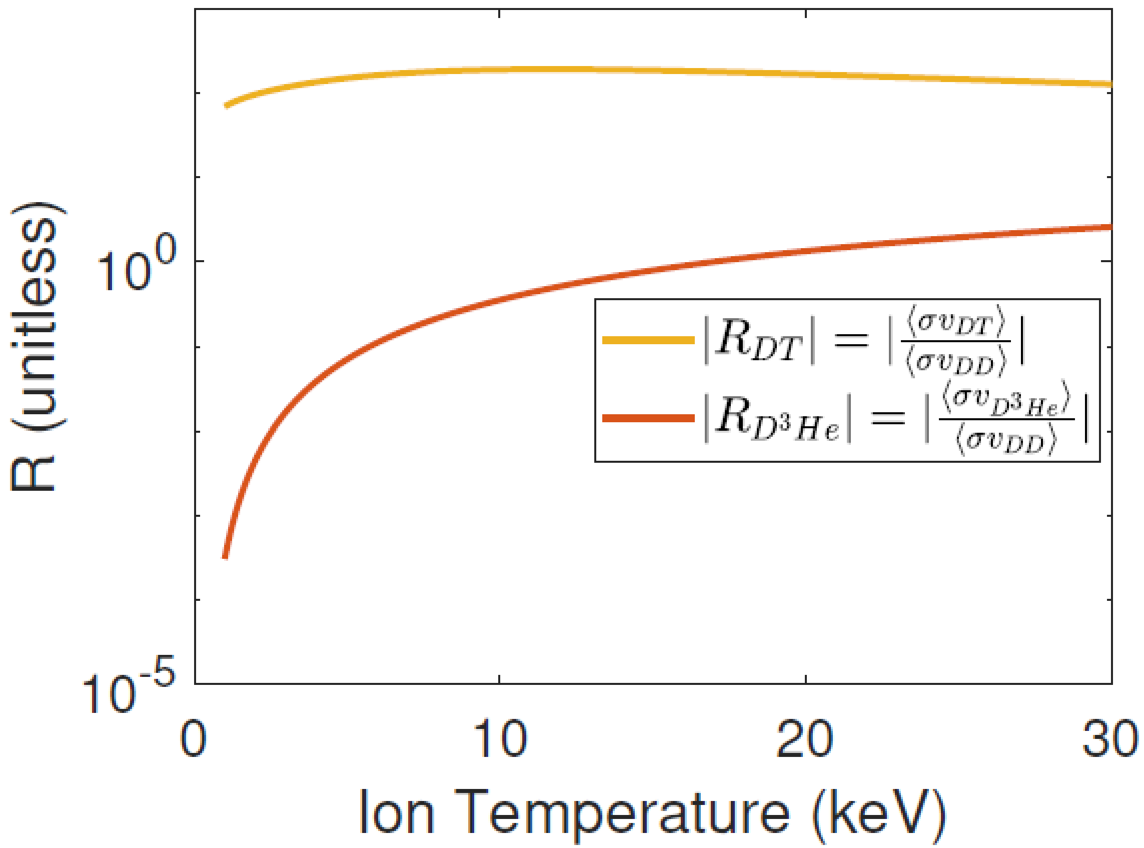
Profile effects serve to increase the effective D3He ion temperature which worsens the discrepancy

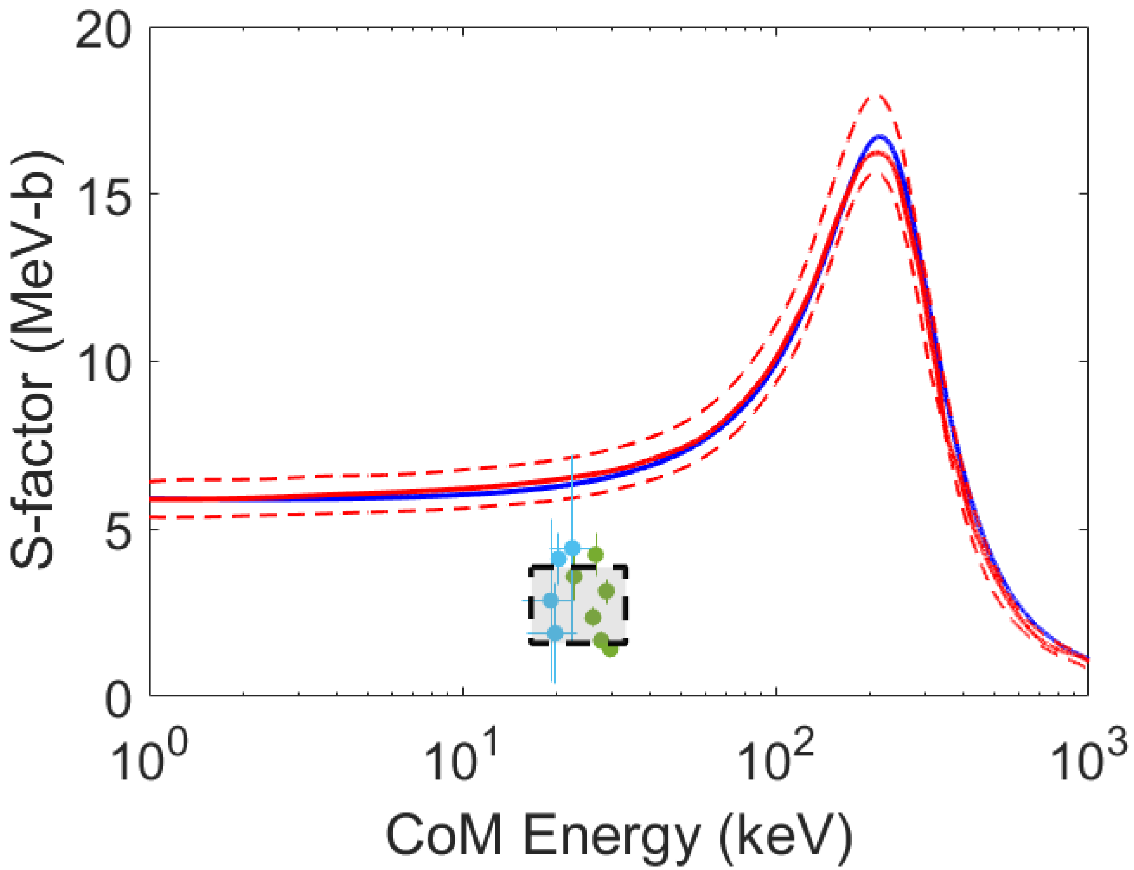


The D3He reactivity increases much more rapidly with temperature than DD. For this reason D3He-p are on average emitted from high temperature regions and times in the implosion, and the effective emission averaged temperature for D3He is higher than the DD temperature, which was used for this analysis.

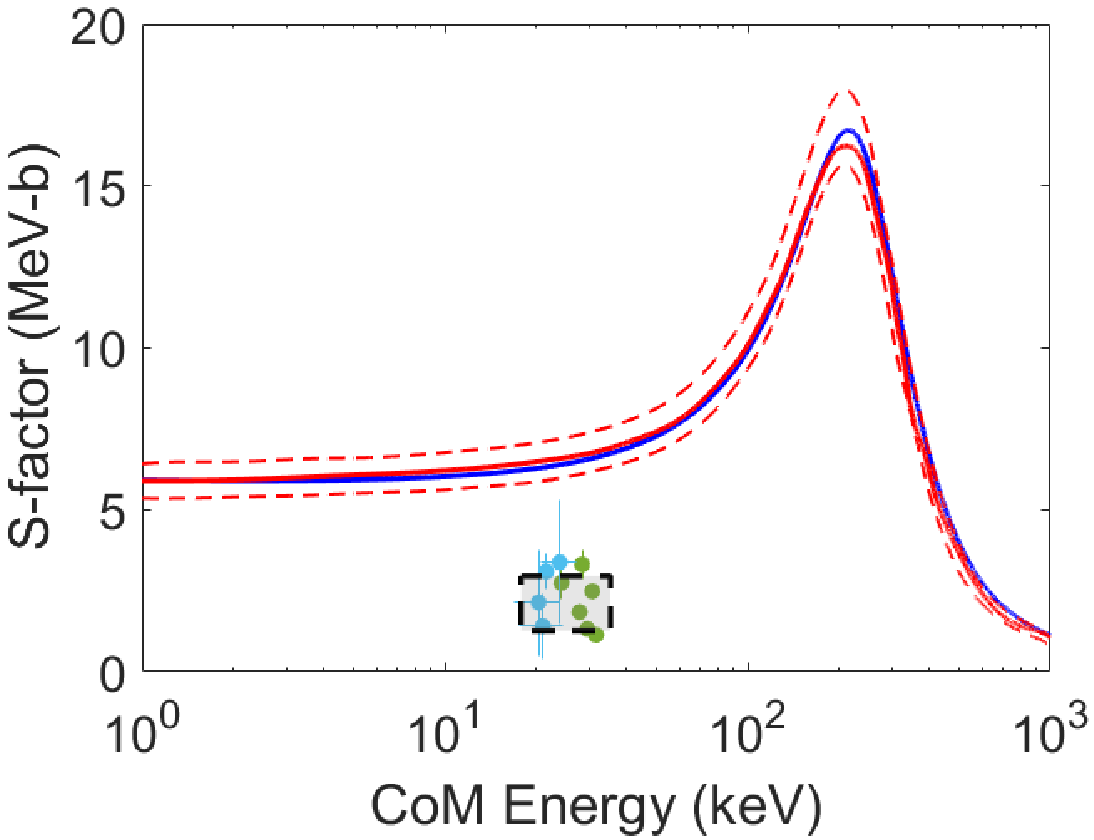
Increasing the temperature to try and account for this worsens the discrepancy.

Profile effects serve to increase the effective D3He ion temperature which worsens the discrepancy

Using TDDn



Using 1.1*TDDn



Species separation as observed in shock driven omega experiments also serves to worsen the discrepancy

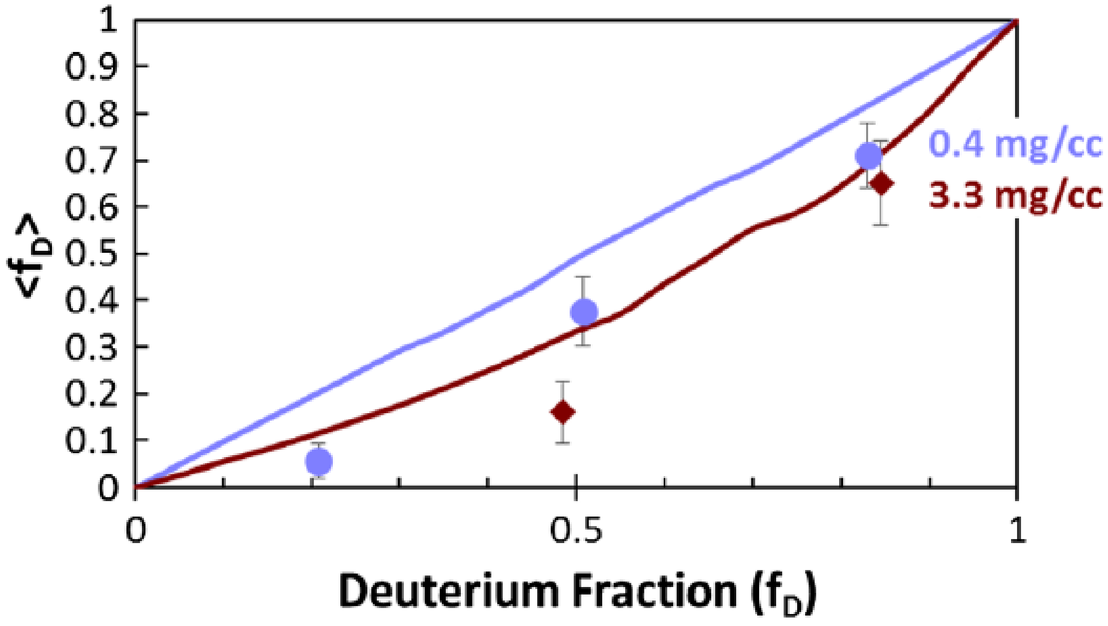


FIG. 4 (color online). "Burn-averaged deuterium fraction" $\langle f_D \rangle$ evaluated from the experiments for low-density (blue) and high-density (red) implosions, compared to 1D-clean simulations (lines). Simulated values for $\langle f_D \rangle$ differ slightly from the fuel f_D due to differences in the D^3He and DD reactivity. Reduction of the deuterium in the core prior to burn is inferred for all implosions.

Rinderknecht et. al., PRL 114, 025001 (2015)

In omega shock-driven experiments the D fraction in the hot-spot is consistently observed to be suppressed relative to the initial fill value.

Decreasing the effective D fraction directly increases the inferred reactivity, and therefore the S-factor, worsening the agreement.

$$\langle \sigma v \rangle_{D3Hep} = \frac{1}{2} \frac{\boldsymbol{Y_{D3Hep}}}{\boldsymbol{Y_{DDn}}} \frac{f_D}{1 - f_D} \langle \boldsymbol{\sigma v} \rangle_{\boldsymbol{DDn}}$$

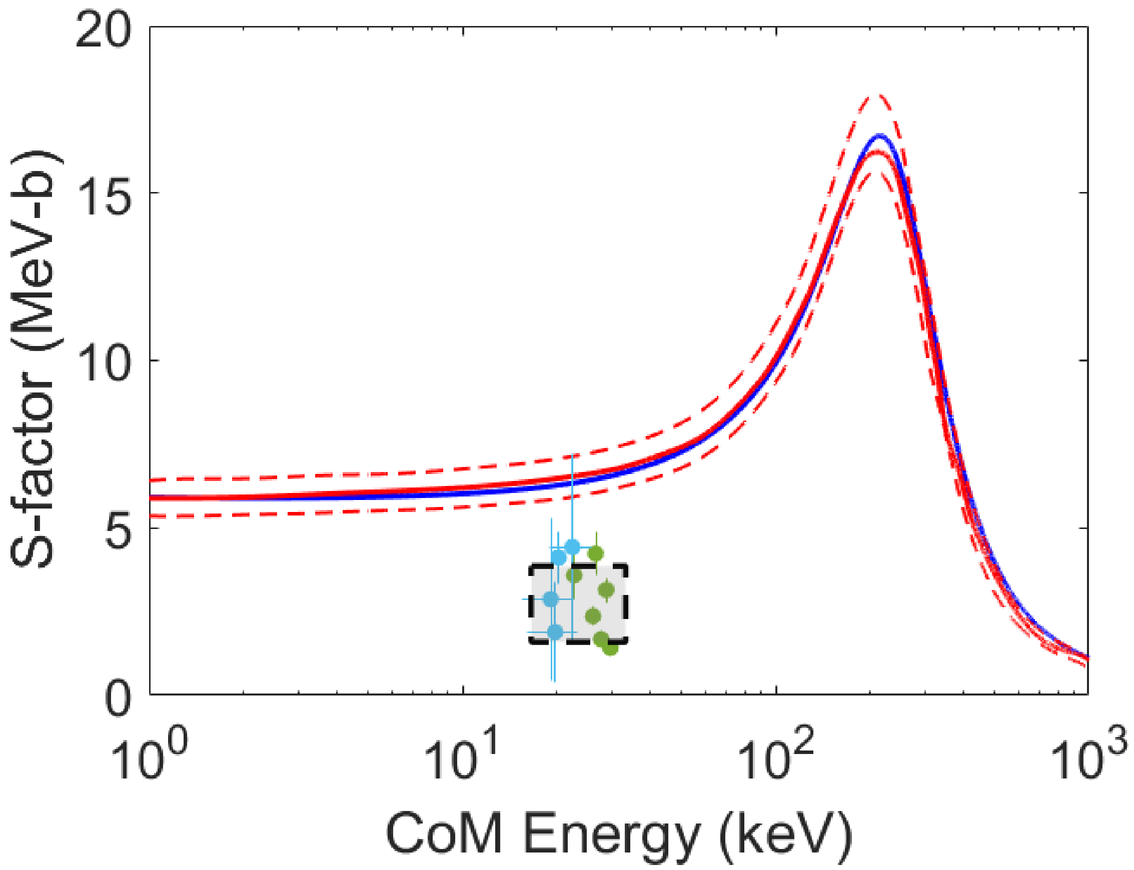
Flows do have a favorable impact, but the required magnitude is unphysically large

$$T_{ntof,12} = \langle T_{12} \rangle + M_{12}\sigma_{vlos}^2$$

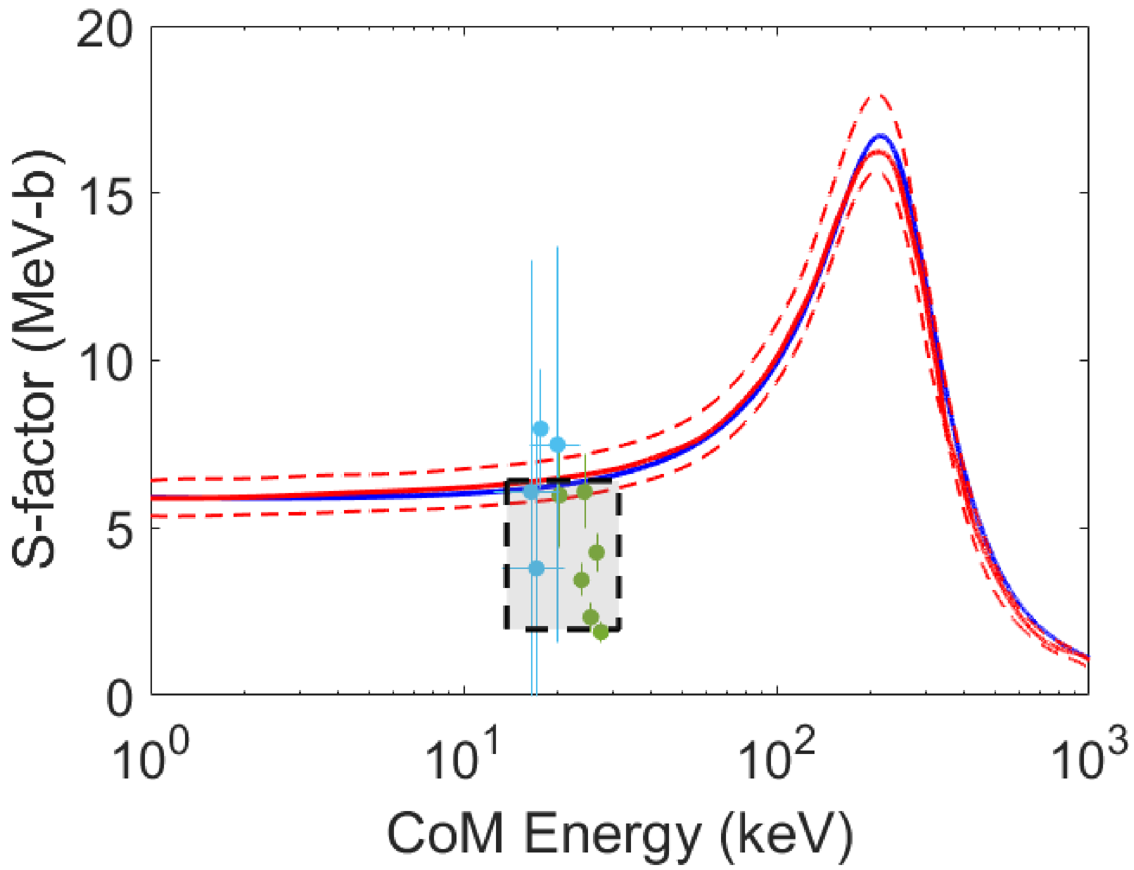
- For a radial flow the flow variance along a line of sight is $\sigma_{vlos}^2 = \frac{1}{3} v_r^2$
- To bring the measurements into agreement the “true” $\langle T_{12} \rangle$s must be 0.5 keV less than the NToF values. This corresponds to a flow velocity of 200 km/s.
- The maximum simulated flow value was for the most asymmetric implosion N150809, for which the vr = 110 km/s, nearly a factor of 2 lower.
- The mean implosion velocity is using the PTOF measured nuclear bang time is 95 km/s and according to my rhoR fit the shell velocity between shock and compression is also $\sim$100 km/s.
- 200 km/s is a factor of 2 larger than all of these velocities.

Flows do have a favorable impact, but the required magnitude is unphysically large

No flow

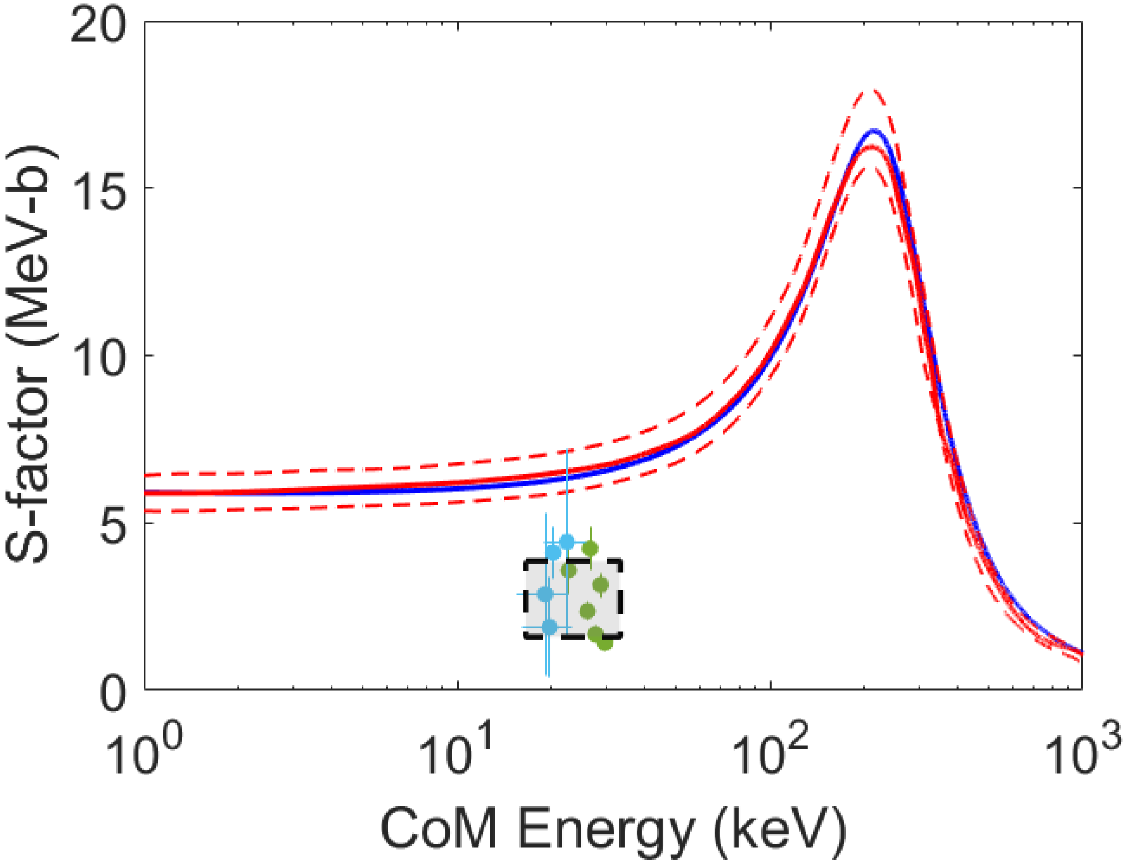


200 km/s flow

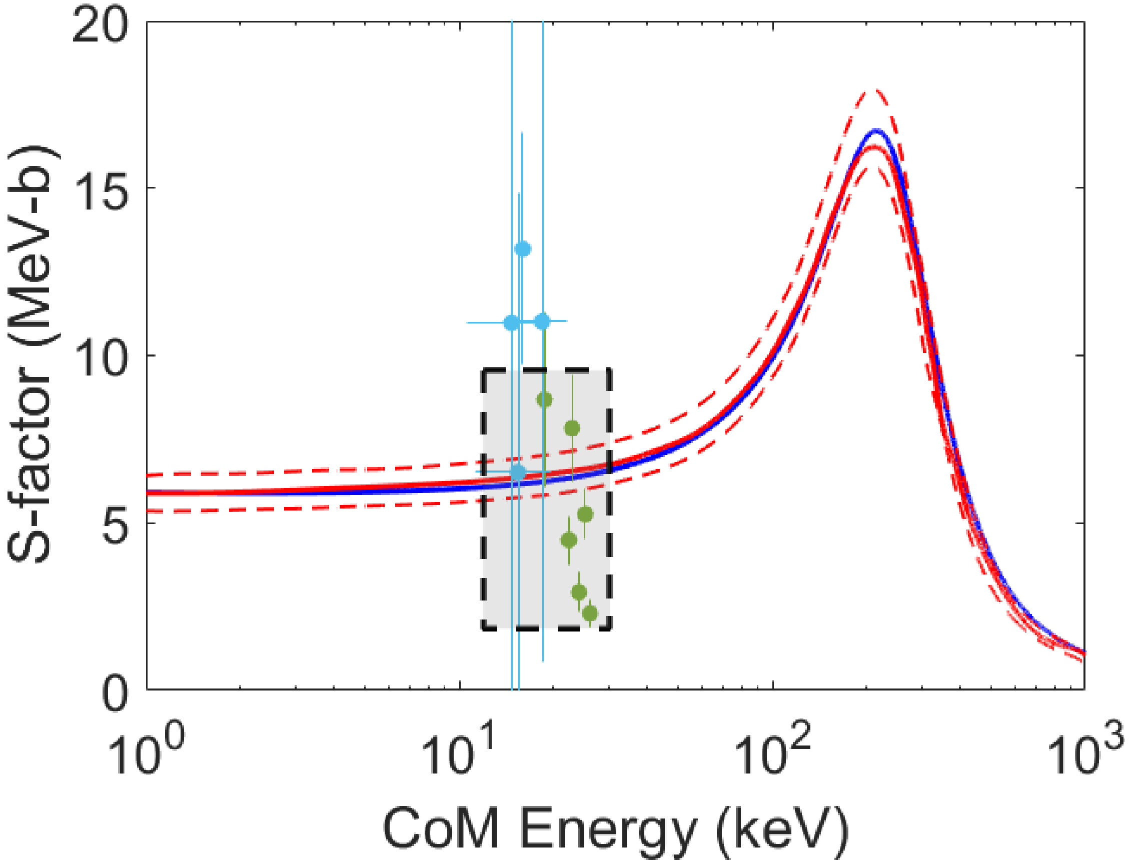


Flows do have a favorable impact, but the required magnitude is unphysically large

No flow

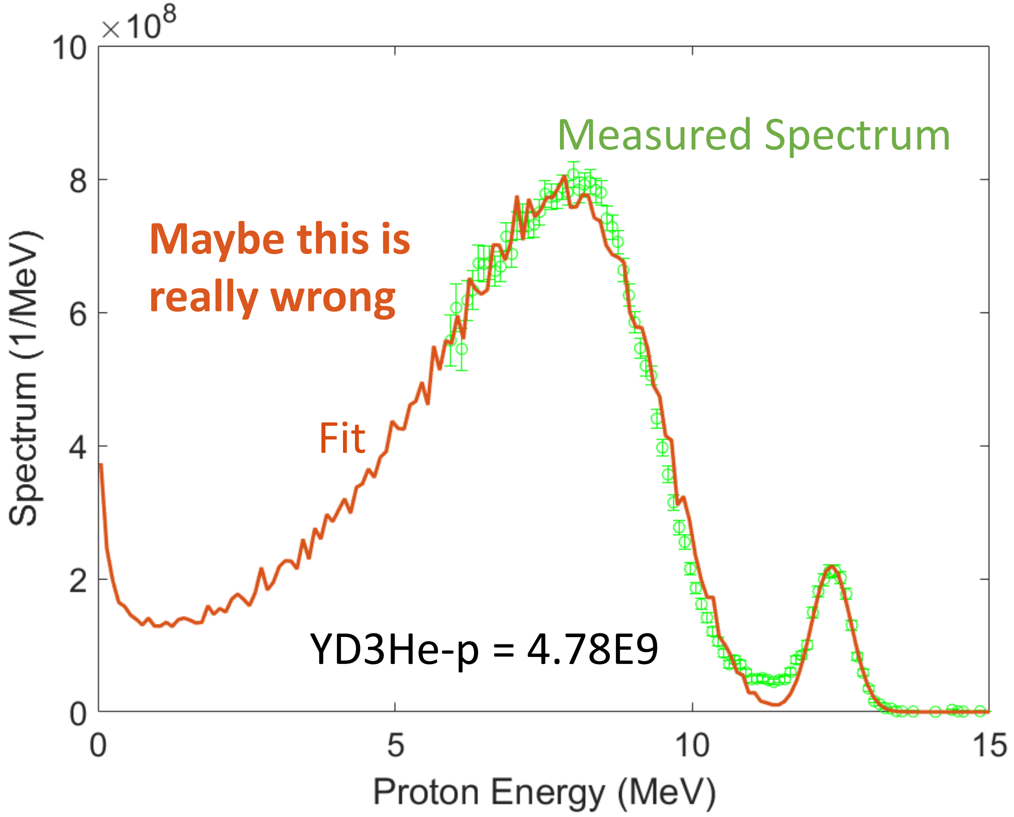


240 km/s flow



Maybe the inferred yield is wrong? For the NIF data it involved a complex model and fit to the data

Fit to WRF spectrum from N150809



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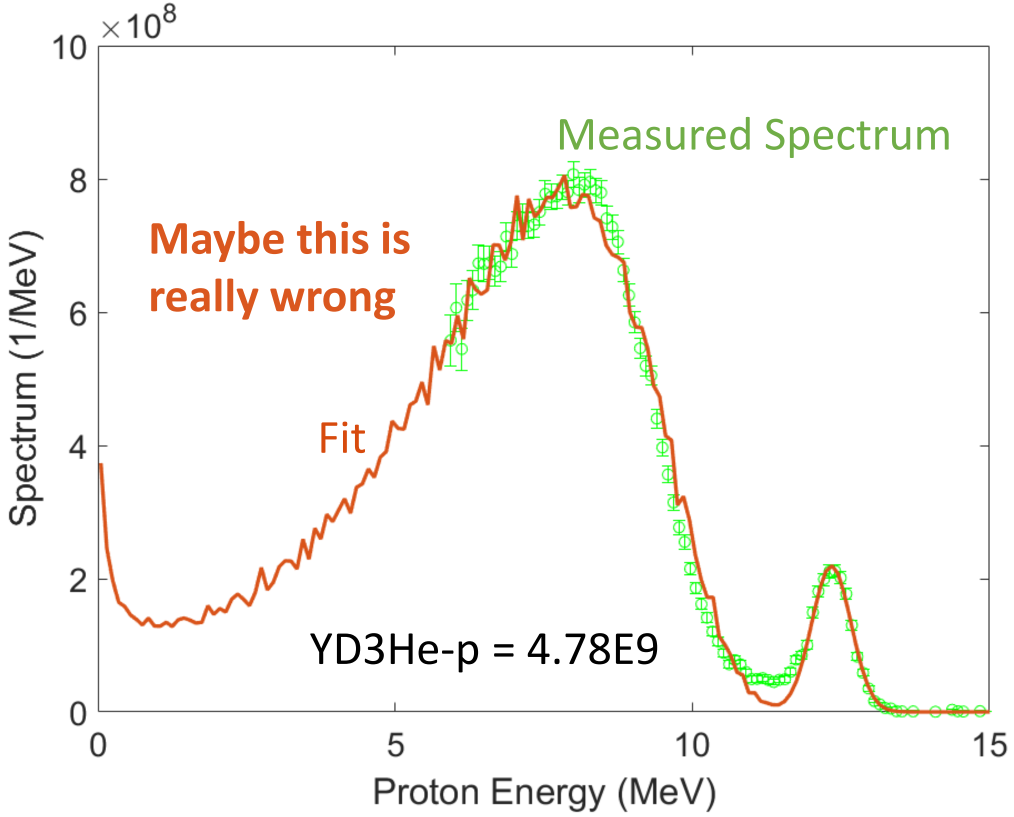
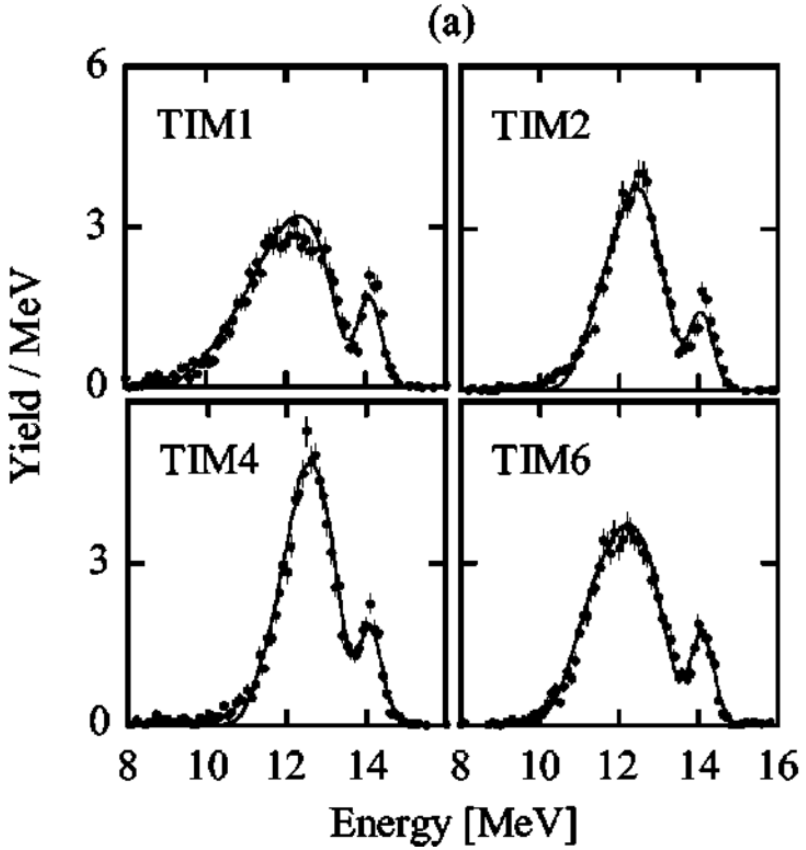


OMEGA D3Hep data

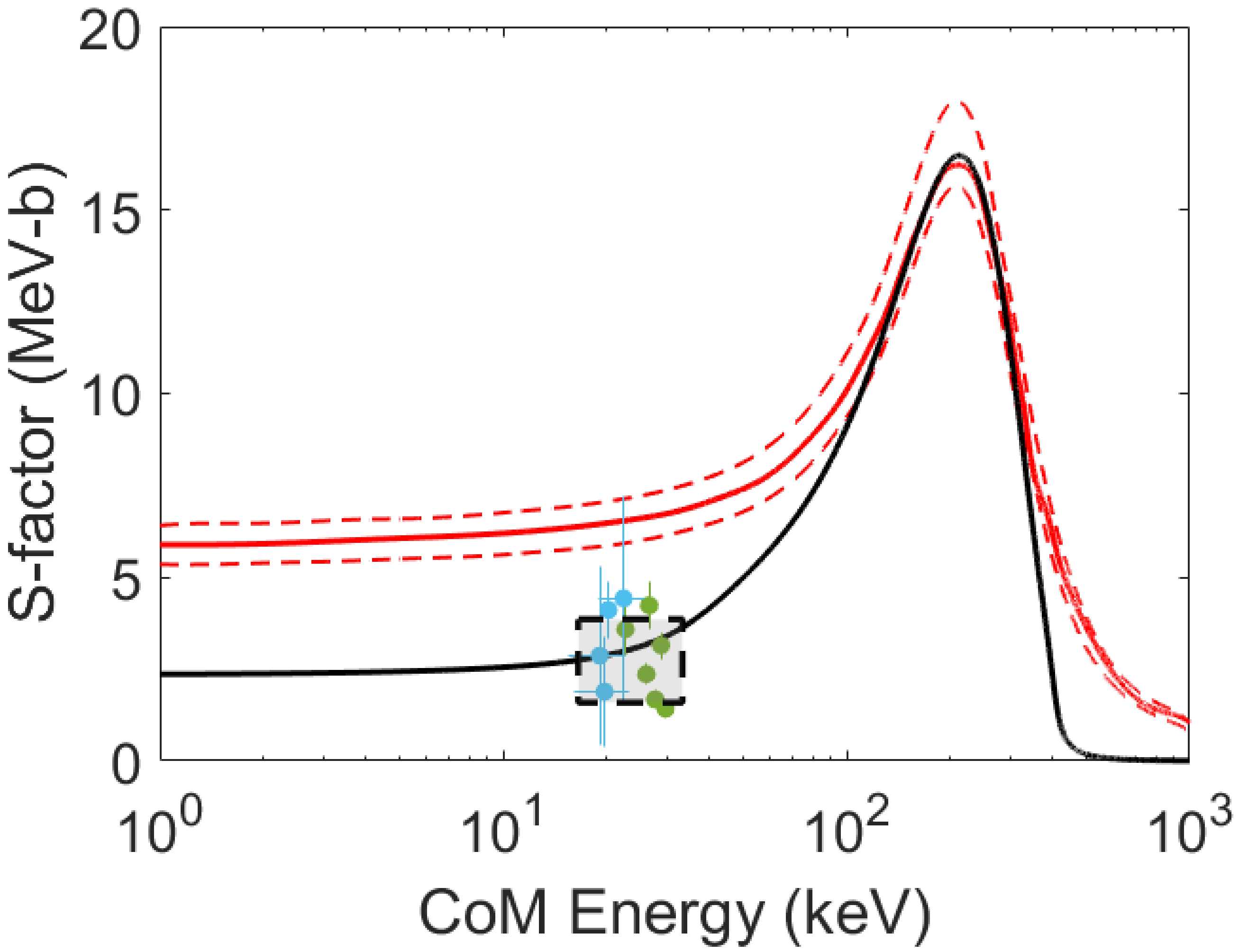


The OMEGA WRF measurements capture the entire compression spectrum and agree with the NIF values

Possible explanations

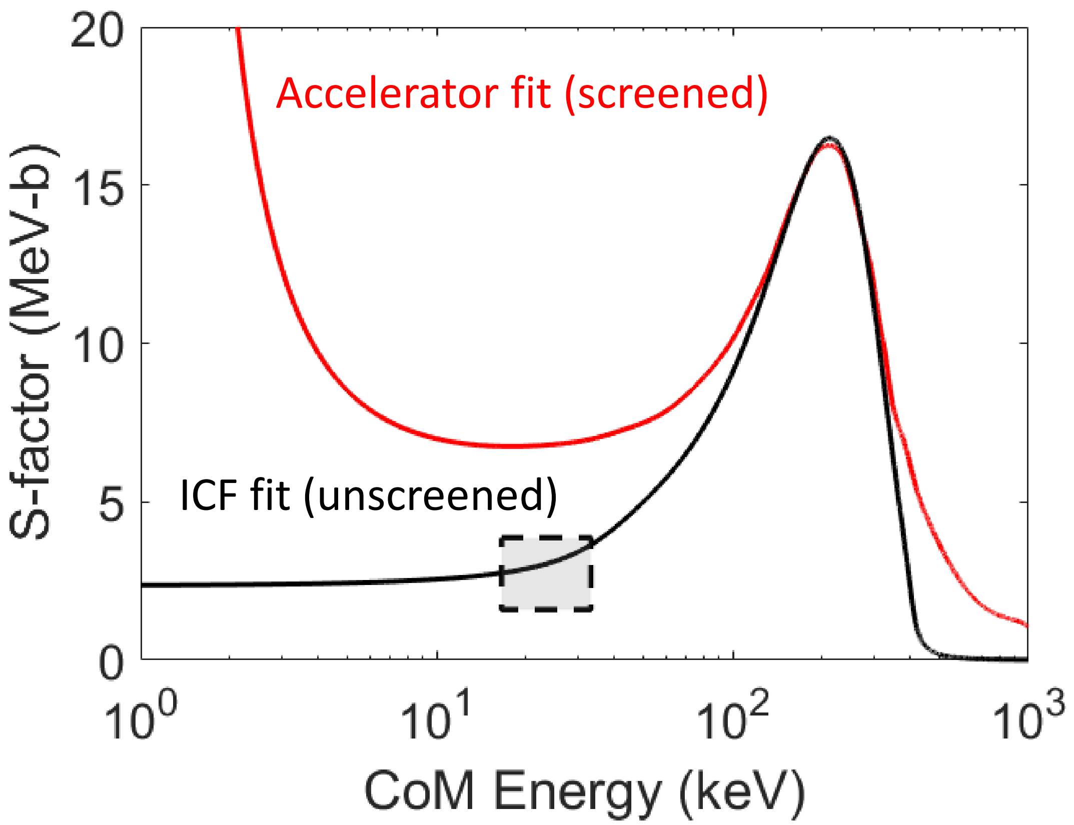
- ~~Thermal decoupling~~ (ion-ion equilibration time too high)
- ~~Profile effects~~
- ~~Species separation~~
- ~~Flows~~
- ~~D3He-p yield measurement is wrong~~
- **Fits to the accelerator data are wrong?**

Using the ICF value as the "true" unscreened S-factor far from resonance and the accelerator data at resonance a Breit-Wigner distribution was fit to the data



- This fit does a good job capturing both the accelerator data near resonance and the ICF data at lower energy
- It does a poor job matching the accelerator data above resonance

The Breit-Wigner fit can be compared to the screened accelerator data to estimate the screening factor vs CoM energy



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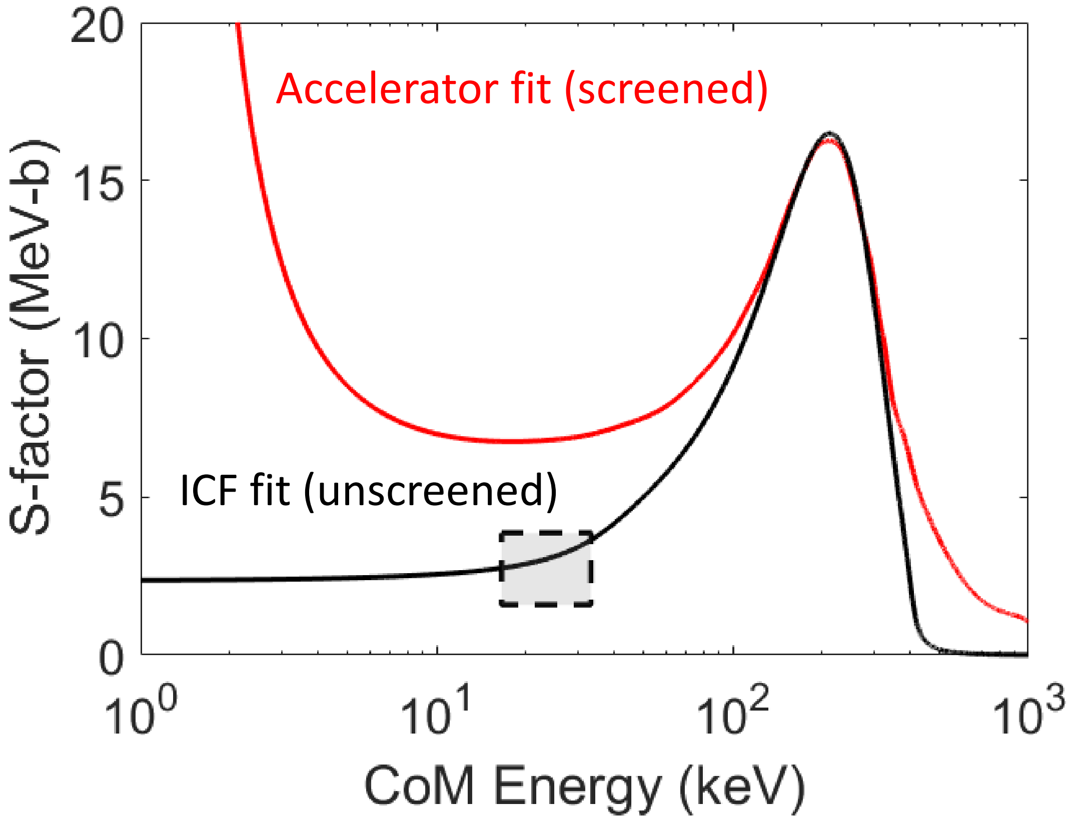
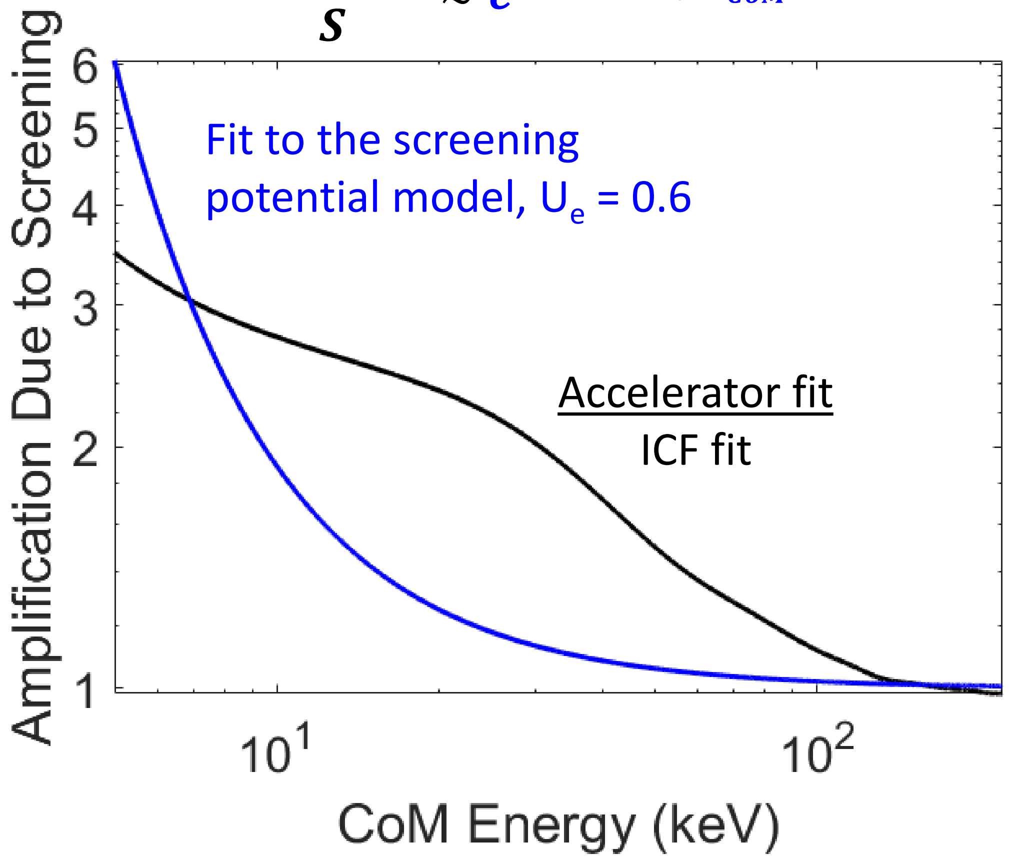


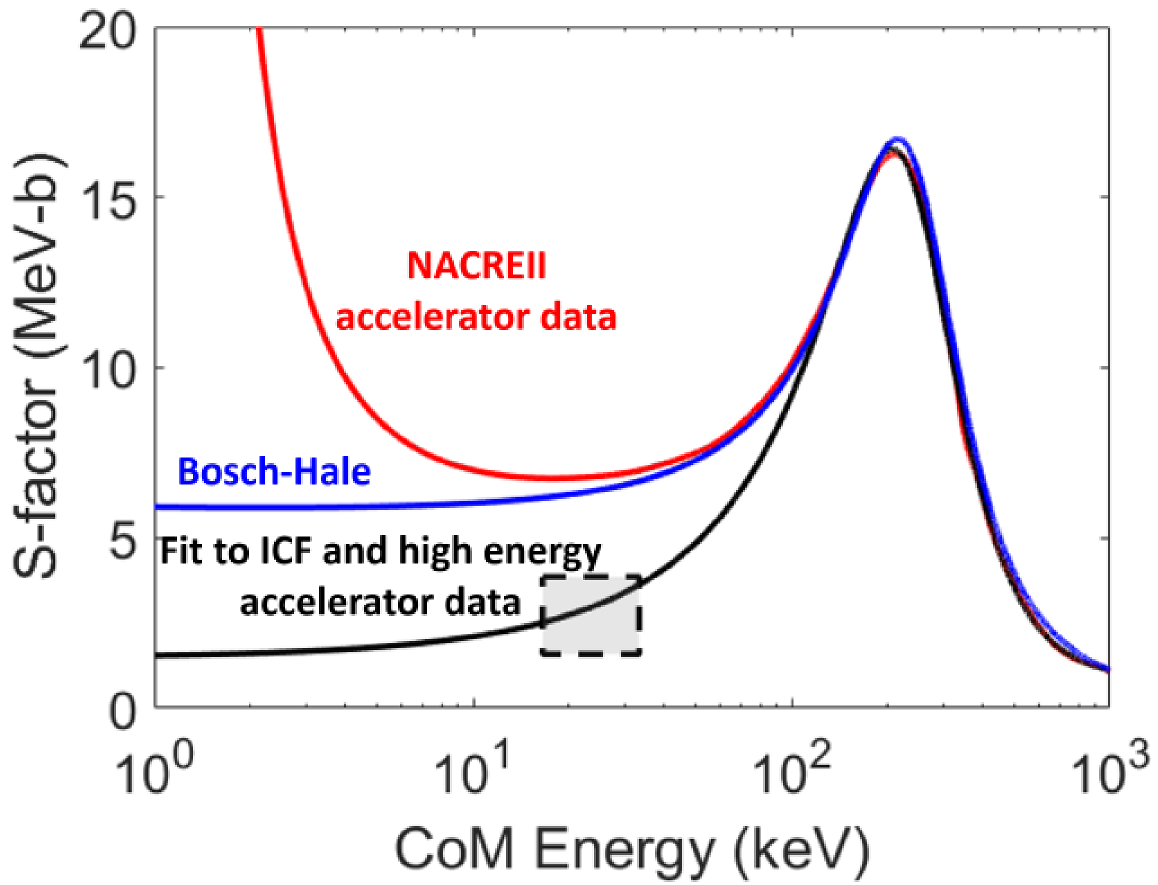
$$\frac{S_{screened}}{S} \approx e^{\frac{1}{2}\sqrt{\frac{E_G}{E_{CoM}}}U_e / E_{CoM}}$$

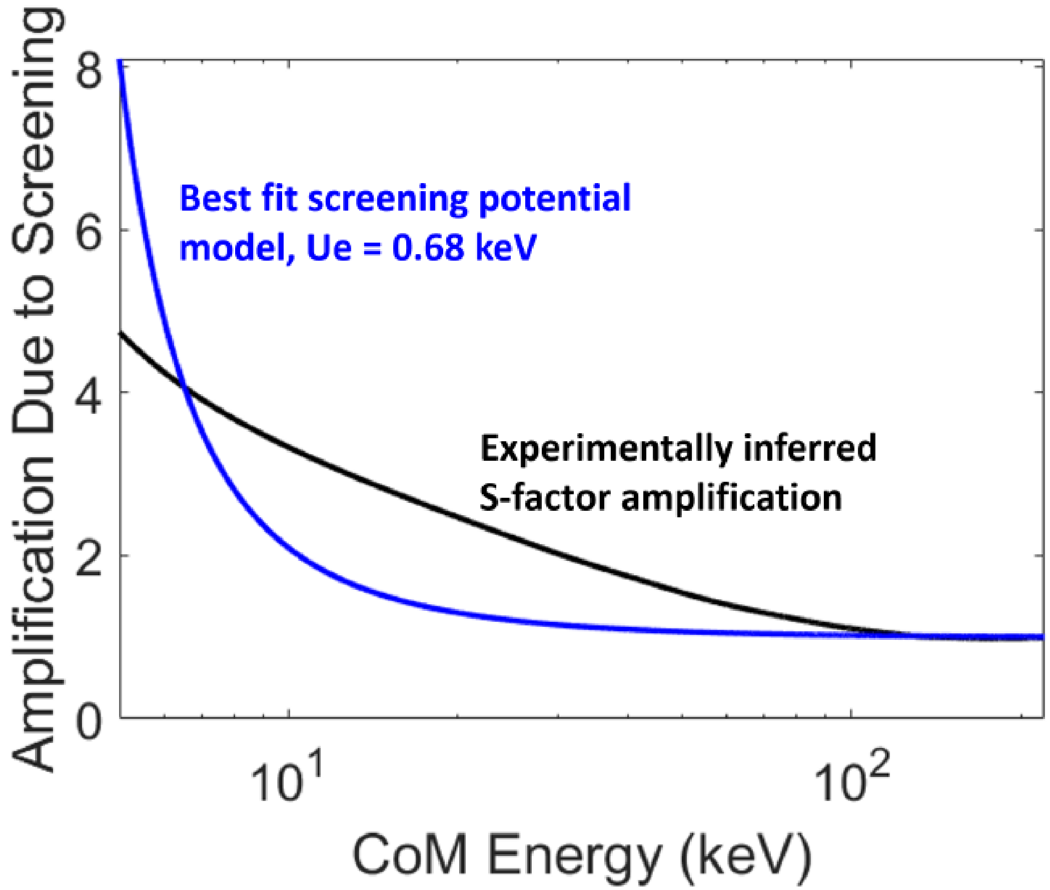


The screening potential model does a poor job fitting the inferred screening factor, and the fit value of 0.6 is much larger than the theoretical value of 0.11.

The combined ICF and resonant accelerator data can also be fit to a pade polynomial expansion as is used for the Bosch-Hale parametrization.

$$S = \frac{A1 + E(A2 + A3E)}{1 + E(B1 + E(B2 + B3E))}$$





N161204-001

NP3 Tion = 3.078+/-0.003+/-0.270 keV

E3 Tion = 3.032+/-0.002+/-0.270 keV

A3 Tion = 2.937+/-0.007+/-0.270 keV

SP3 Tion = 3.055+/-0.005+/-0.270 keV

stdev= 0.062 keV

N151221-001

E3 Tion = 2.280+/-0.002+/-0.270 keV

A3 Tion = 2.238+/-0.010+/-0.270 keV

SP3 Tion = 2.304+/-0.012+/-0.270 keV

stdev = 0.033 keV

N160410-001

E3 Tion = 2.322+/-0.005+/-0.270 keV

A3 Tion = 2.312+/-0.008+/-0.270 keV

SP3 Tion = 2.376+/-0.009+/-0.270 keV

stdev = 0.034 keV

N150809-001

E3 Tion = 2.394+/-0.004+/-0.270 keV

A3 Tion = 2.340+/-0.018+/-0.270 keV

SP3 Tion = 2.811+/-0.018+/-0.270 keV

stdev = 0.258 keV