Experiment and Phenomenology for Reactions with 3 Bodies in the Final State

Ohio University

13 March 2017

INT Program INT 17-1A: Nuclear Reactions, Workshop Week 3:
A Symbiosis between Experiment, Theory and Applications

Overview of Presentation

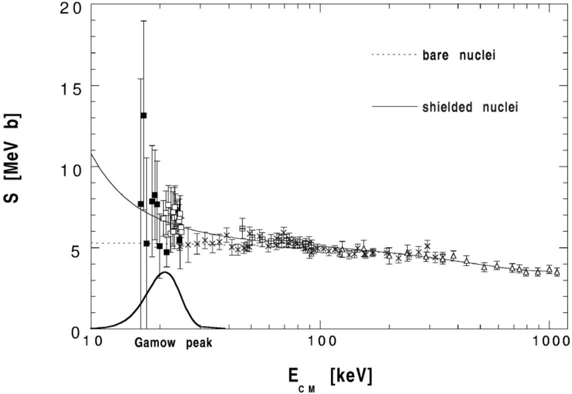
- T$(t, 2n)\alpha$ Inertial Confinement Fusion Experiments
- T$(t, 2n)\alpha$ Neutron Energy Spectrum
- T$(t, 2n)\alpha$ Thermonuclear Reaction Rate
- T$(t, 2n)\alpha$ Neutron Spectrum Temperature Dependence
- T$(^3\mathrm{He}, np)\alpha$ and $^3\mathrm{He}(^3\mathrm{He}, 2p)\alpha$ Experiments
- Conclusions and Outlook

Motivation and Background

- Study reaction mechanism: ^{5}He and di-neutron correlations
- R-Matrix description of 3-particle final states
- Study mirror symmetry
- Demonstrate measurements of charged-particle reaction rate in plasma
- The cross section and neutron spectrum are important for inertial confinement fusion
- $^{3}\mathrm{He}(^{3}\mathrm{He}, 2p)\alpha$ is an important fusion reaction in our sun

$^3\mathrm{He}(^3\mathrm{He}, 2p)\alpha$

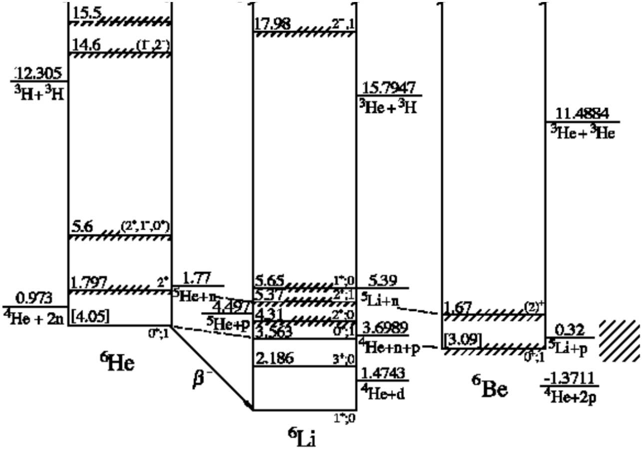
Gran Sasso Experiment: Bonetti *et al.*, Phys. Rev. Lett. **82**, 5205 (1999).



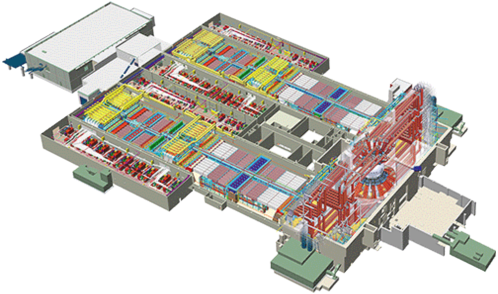
Potential Questions:

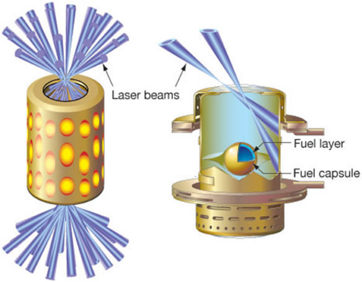
- Electron Screening Effects?
- Resonances?

$A = 6$ Isobar Diagram



National Ignition Facility





images courtesy LLNL

Similar capabilities exist at the Laboratory for Laser Energetics (LLE) at Rochester (Omega Laser), but ≈ 50× less powerful

Unique Features of ICF Environment for Nuclear Physics

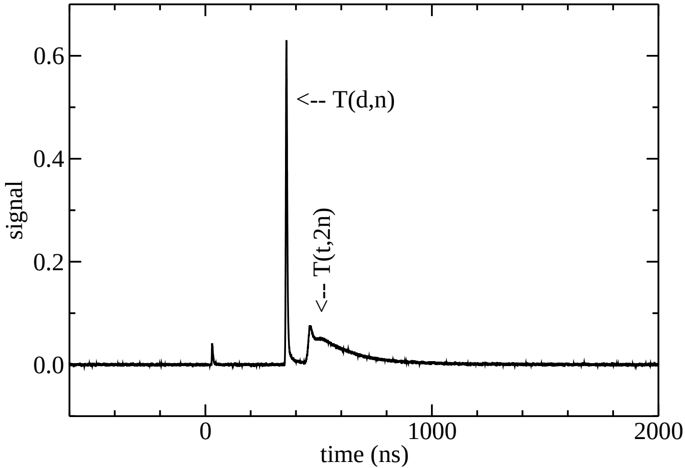
as compared to accelerator-based approaches

- Reactions occur in thermonuclear plasma
- Low mass near target
- Sharp time structure (sub-nanosecond)
- Possibility of high neutron fluxes
- Willingness to work with tritium

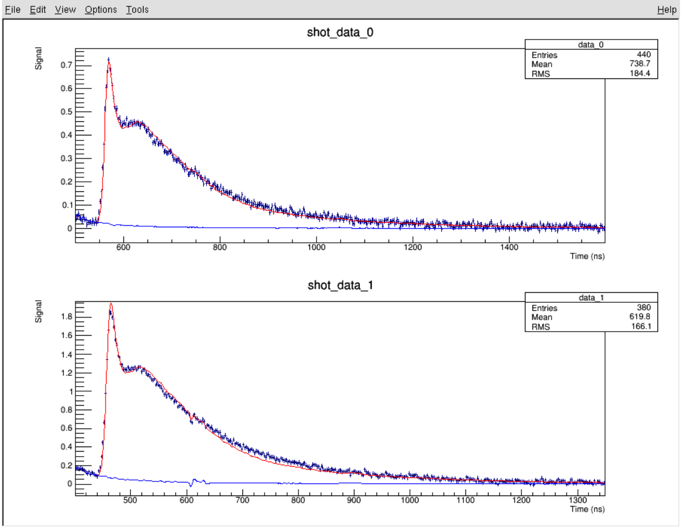
Measurement of the $T(t,2n)\alpha$ at the National Ignition Facility

- Nearly pure tritium gas (0.1% D), low areal density “symcap” (gas-filled plastic capsule)
- $\approx$ 200 ps thermonuclear burn time
- $kT = 3.3(3)$ keV $\quad\rightarrow\quad E_{\text{Gamow}}(\text{T}+\text{T}) = 16$ keV
- 2 organic liquid scintillators (xylene) @ 20 and 22 meters, respectively
- Modeling includes:
  - Instrument Response Function (time response)
  - Scintillator response (efficiency)
  - Attenuation and scattering
  - Thermal broadening
  - Background from T(d,n) (small)

Raw Data from Equator Detector @ 20.1 m



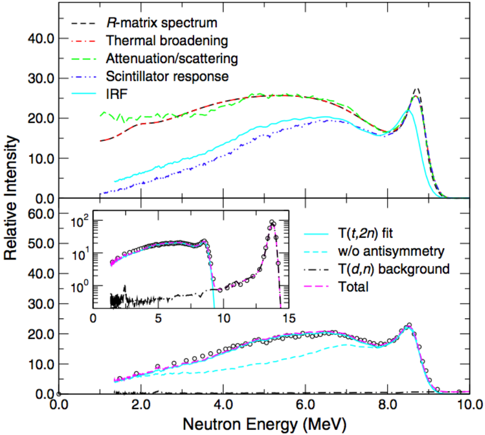
Fits to Time Spectra



data_0	
Entries	440
Mean	738.7
RMS	184.4

data_1	
Entries	380
Mean	619.8
RMS	166.1

$T(t,2n)\alpha$ Neutron Spectrum $E_{c.m.} = 16$ keV

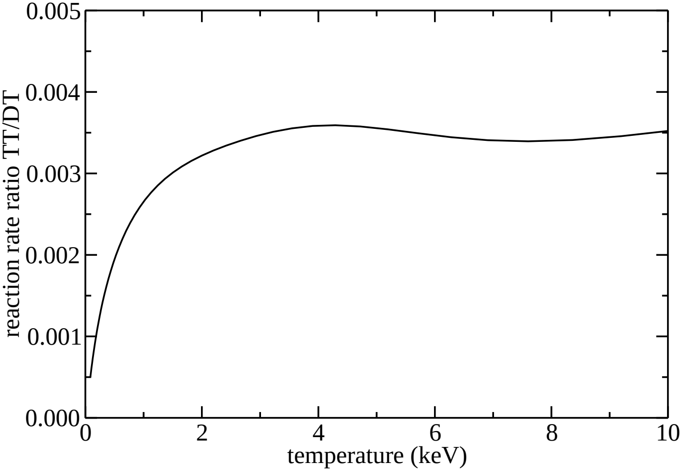


Sayre, Caggiano *et al.*, Rev. Lett. **111**, 052501 (2013). Di-neutron not included.

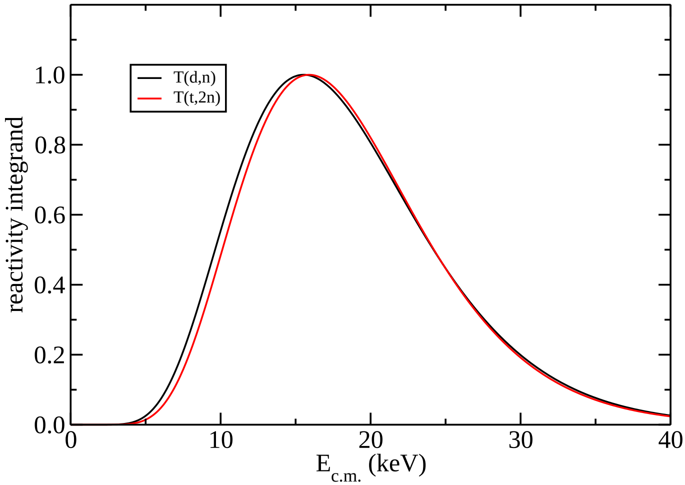
Determination of Thermonuclear Reaction Rate

- Definition:
  $$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu (kT)^3}} \int_0^\infty E\sigma(E) \exp[-E/(kT)]\, dE$$
- Principle of measurement:
  - Measure ratio to $\mathrm{T}(d,n)$ reaction rate (known to $\approx 1\%$)
  - H.-S. Bosch and G.M. Hale, Nucl. Fusion **32** 611 (1992)
  - Assume constant S factor for $\mathrm{T}(t,2n)\alpha$
- Mass spectrometry of capsule fill gas (example capsule):
  - tritium: 99.598(4) %
  - deuterium: 0.082(1) %
  - remainder: protium and ^{3}He
- Yield-weighted ion temperature determination:
  - use width of "14 MeV" neutron peak from $\mathrm{T}(d,n)$
  - Brysk Formula: $\sigma[E_n] \approx \sqrt{\frac{2M_n \langle E_n \rangle}{M_\alpha + M_n}(kT)}$
  - H. Brysk, Plasma Physics **15**, 611 (1973)
  - Actual analysis uses a more sophisticated approach, including, e.g., relativistic kinematics

Reaction Rate Ratio is Insensitive to Temperature



T(d,n) and T(t,2n) Reactivity Integrands for $kT = 3.3$ keV



Systematic Errors Considered:

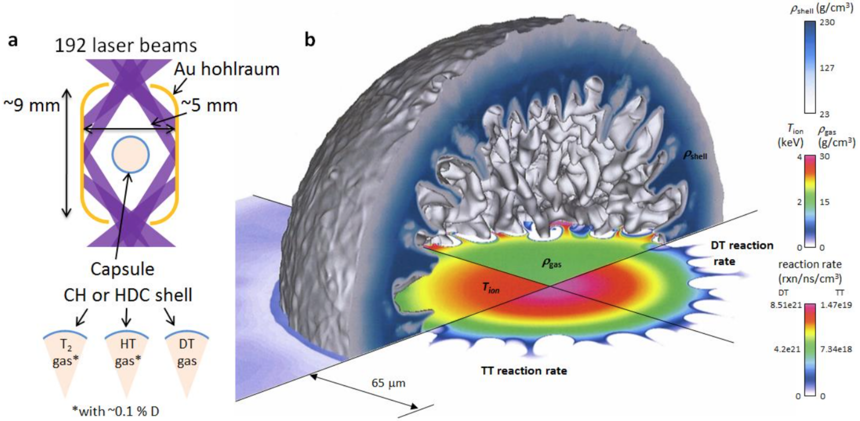
- Fuel mixture uncertainty
- Spectrum fitting
- Ion temperature determination (small)
- Total systematic error is estimated to be 30%

Analysis and Results (Simple Model)

- Numbers of neutrons:
  - $N_{DT} \propto n_D n_T \langle \sigma v \rangle_{DT}$
  - $N_{TT} \propto \frac{n_T^2}{2} \langle \sigma v \rangle_{TT} \times 2$
  - $\frac{N_{TT}}{N_{DT}} = \frac{n_T}{n_D} \frac{\langle \sigma v \rangle_{TT}}{\langle \sigma v \rangle_{DT}}$
  - watch factors of two!
- Spectral fitting (example analysis):
  - $N_{DT} = 3.9 \times 10^{12}$
  - $N_{TT}/N_{DT} = 4.5(4)$
  - $kT = 3.3(3)$ keV (burn-weighted)
- $S(16 \text{ keV}) \approx 200$ keV-b

More Sophisticated Analysis

considering time and spatial dependence of density, temperature, . . .

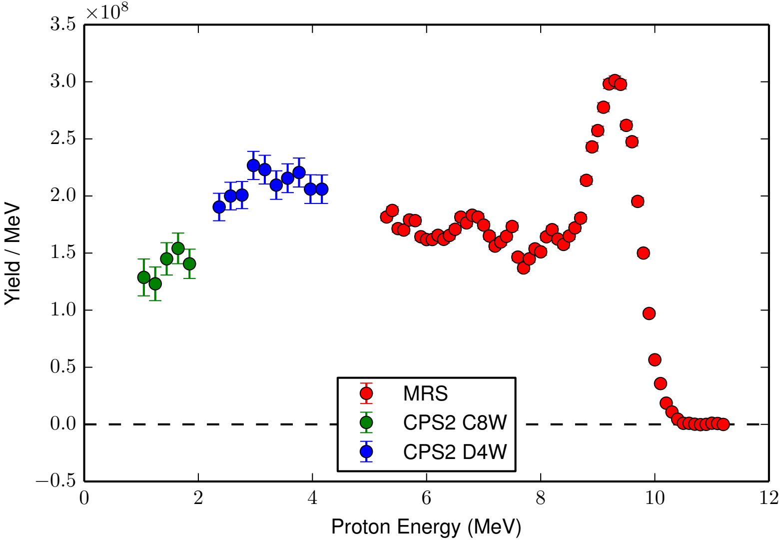


Dan Casey (LLNL)

$\mathrm{T}(^3\mathrm{He}, np)\alpha$, $\mathrm{T}(^3\mathrm{He}, d)\alpha$, and $^3\mathrm{He}(^3\mathrm{He}, 2p)\alpha$

- Campaign of measurements are underway by Maria Gatu-Johnson, Alex Zylstra, Johan Frenje *et al.* (MIT/LLNL/Rochester/...)
- Requires proton detection via "Wedge Range Filters"
- Allows tests of isospin and mirror symmetry.
- $^3\mathrm{He}(^3\mathrm{He}, 2p)\alpha$ measured at NIF last month (looking for temperature dependence of proton energy spectrum)
- Accurate temperature measurement is not possible at this time.

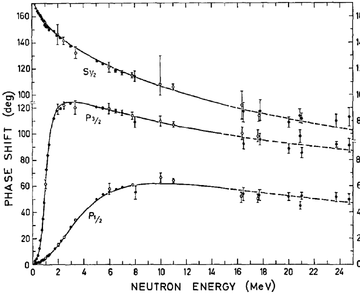
$T(^3\mathrm{He}, np)\alpha$ Proton Spectrum



How should one try to analyze or understand reactions with three particles in the final state?

- Ab-initio theory is not there yet.
- My interested: Phenomenology.
- Ideally: Unitary, includes known 2-body channel information, angular momentum conservation,...
- R-matrix?

Two-Body Channels are Generally Well Known



$n - \alpha$ R-matrix parameters: Stammbach and Walter (1972).

Single (total) Energy Analysis is “Solved”

Carl Brune, Dan Sayre, Jac Caggiano, Andy Bacher, Gerry Hale, Mark Paris, Phys. Rev. C **92**, 014003 (2015).

- Three-body final state treated in Faddeev-inspired approach
- Kinematics (recoil) is more complicated
- Angular correlation effects on spectrum
- Identical particles / antisymmetrization
- F.C. Barker formalism + angular momentum coupling + antisymmetrization
  - D.P. Balamuth, R.W. Zurmühle, and S.L. Tabor, Phys. Rev. C **10**, 975 (1974).
  - D.F. Geesaman *et al.*, Phys. Rev. C **15**, 1835 (1977).
  - H.O.U. Fynbo *et al.*, Phys. Rev. Lett **91**, 082502 (2003).

Some Formulas

- Our form for the matrix element:

$$\mathcal{M}_{\nu_1\nu_2} = \sum_c u_c(12) f^{lJ}_{\nu_1\nu_2}(\Omega_1, \Omega_{23}) - u_c(21) f^{lJ}_{\nu_2\nu_1}(\Omega_2, \Omega_{13})$$

- u_c is given by an R-matrix expression:

$$u_c(12) = \left[\frac{P_1 P_{23}}{p_1 p_{23}}\right]^{1/2} e^{i(\omega_1 - \Phi_1)} e^{i(\omega_{23} - \Phi_{23})} \frac{\sum_\lambda \frac{A_{c\lambda}\gamma_{c\lambda}}{E_{c\lambda} - E_{23}}}{1 - [S_{23} - B_c + iP_{23}]R_c}$$

- $f^{lJ}_{\nu_1\nu_2}$ contains the spin and angular information:

$$f^{lJ}_{\nu_1\nu_2}(\Omega_1, \Omega_{23}) = \sum_{m, m_l, m_l'} \frac{(-1)^{J+m}}{\sqrt{2J+1}} \langle l m_l \frac{1}{2} \nu_1 | J m \rangle \langle l m_l' \frac{1}{2} \nu_2 | J {-m} \rangle Y_{l m_l}(\hat{\boldsymbol{p}}_1) Y_{l m_l'}(\hat{\boldsymbol{p}}_{23})$$

- The particle distribution is given by

$$\frac{d^3 N}{dE_i \, \Omega_i \, d\Omega_j} = \sum_{\nu_1, \nu_2} |\mathcal{M}_{\nu_1\nu_2}|^2 \, p_i p_{jk} \mathcal{J}_{ijk}$$

- A 0^+ ($l = 0$) initial $t + t$ state is assumed, and $c = 1/2^+$, $1/2^-$, $3/2-$ $n + \alpha$ or an $l = 0$ spin-singlet di-neutron state.

Outlook

- Measurements of particle spectra and cross sections for the $\mathrm{T}(t,2n)\alpha$, $\mathrm{T}(^3\mathrm{He},np)\alpha$, and $^3\mathrm{He}(^3\mathrm{He},2p)\alpha$ reactions have been recently completed or are in progress.
- An interesting temperature dependence of the $\mathrm{T}(t,2n)\alpha$ neutron energy spectrum has been observed.
- Can a scheme for doing energy-dependent R-matrix analyses of these reactions be devised?
- Many more applications: 2-nucleon emission, $^{11}\mathrm{B}(p,3\alpha)$, β decays

Thanks to collaborators:

- D.T. Casey, J.A. Caggiano, R. Hatarik, D.P. McNabb, D.B. Sayre,... (Lawrence Livermore National Lab)
- G.M. Hale, M.W. Paris. A.B. Zylstra,... (Los Alamos National Lab)
- J.A. Frenje, M. Gatu-Johnson, C.E. Parker,... (MIT)
- A.D. Bacher (Indiana), M. Couder and M. Wiescher (Notre Dame)