Studies of the T + T reaction at JET
using neutron time-of-flight spectrometry

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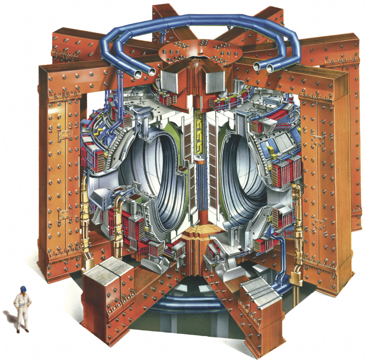
Contents

Introduction

Fusion as a source of energy

Considerable efforts for controlled fusion

- Inertial confinement
- Magnetic confinement (Joint European Torus)

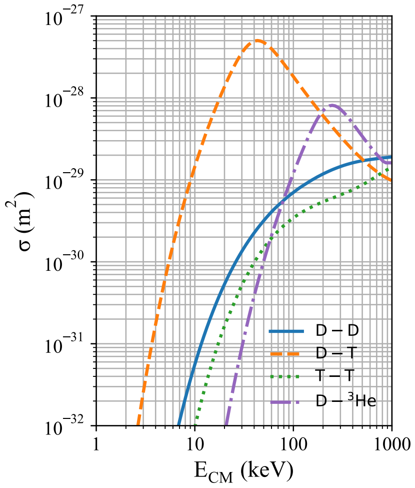


Considerable efforts for controlled fusion

- Inertial confinement
- Magnetic confinement (Joint European Torus)

Table: Fusion reactions, Q-values, and the neutron energy.

#	Reaction	Q [MeV]	E_n [MeV]
1.	D + D → p + T	4.03	N/A
2.	D + D → ^{3}He + n	3.27	2.45
3.	D + T → ^{4}He + n	17.59	14.03
4.	**T + T → ^{4}He + 2n**	**11.33**	**(0, 9.42)**
5.	^{3}He + D → ^{4}He + p	18.35	N/A



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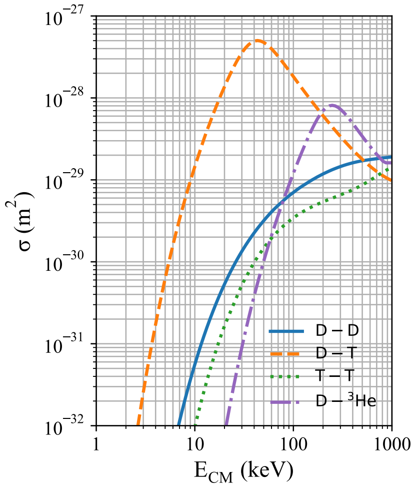
Motivation

- Modelling the TT neutron spectrum
- Radiation protection / activation of materials
- Mirror reaction ${}^3He({}^3He, 2p)\alpha$
- Solar proton-proton chain



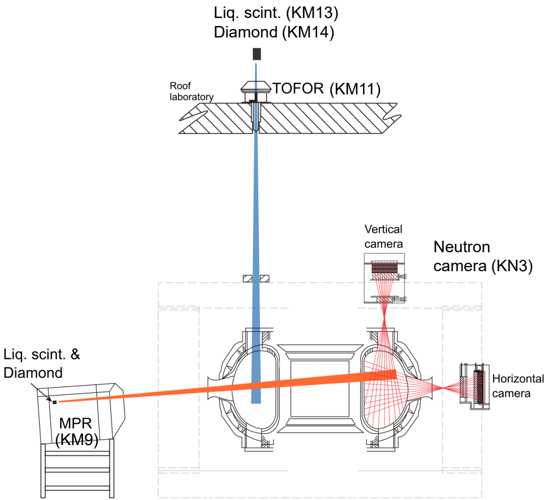
Neutron diagnostics

Neutron energies from three reactions

- DD: 2.45 MeV
- DT: 14.03 MeV
- **TT: 0-9.42 MeV**

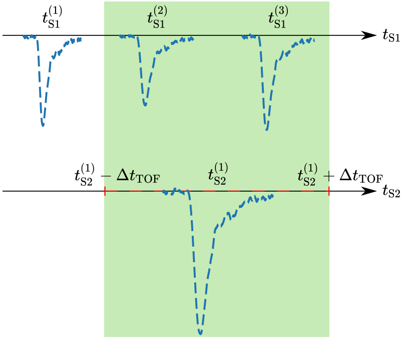
Carry information from fusion plasma

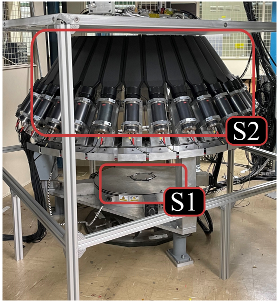
- Reaction rate (neutron counters)
- Plasma spatial distribution (neutron camera)
- Fuel ion temperature (neutron spectrometers)
- Fuel ion ratio, n_T/n_D (spectrometers, counters with energy thresholds)



Time-of-flight (TOF) neutron spectrometer

- Two sets of plastic scintillators (5 S1, 32 S2)
- Find coincidences
- $t_{\text{TOF}} = t_{\text{S2}} - t_{\text{S1}}$





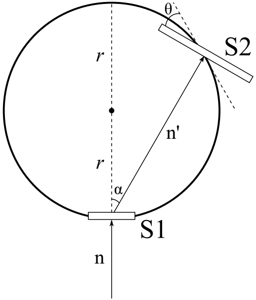
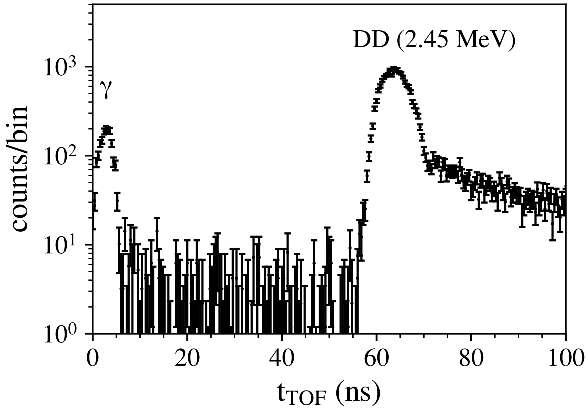


Figure: Picture of TOFOR with S1 and S2 sets indicated (left panel) and a sketch of the same setup with $\alpha = 30°$, $\theta = 5°$ and $r = 705$ mm (right panel).

TOF spectra from three fuel mixtures

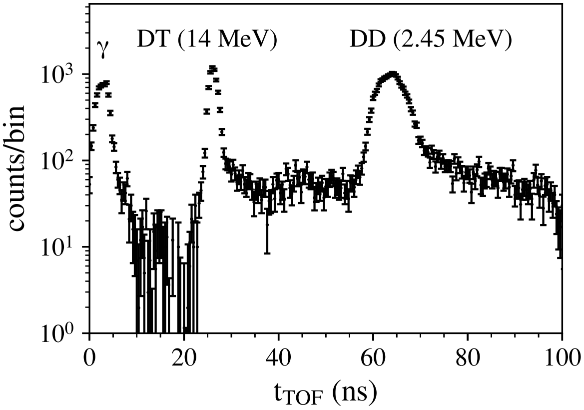
- Deuterium plasma



Spectral features

TOF spectra from three fuel mixtures

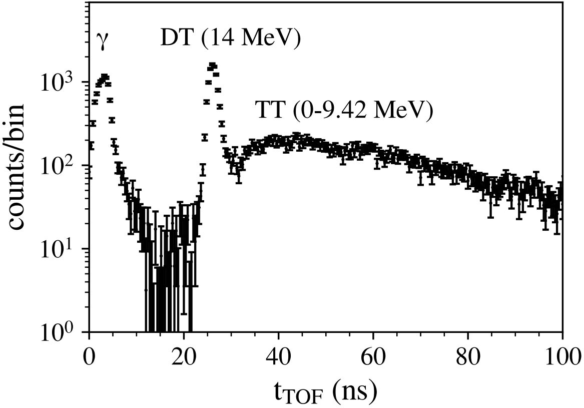
- Deuterium plasma
- Deuterium dominated plasma D(T)



Spectral features

TOF spectra from three fuel mixtures

- Deuterium plasma
- Deuterium dominated plasma D(T)
- Tritium dominated plasma T(D)



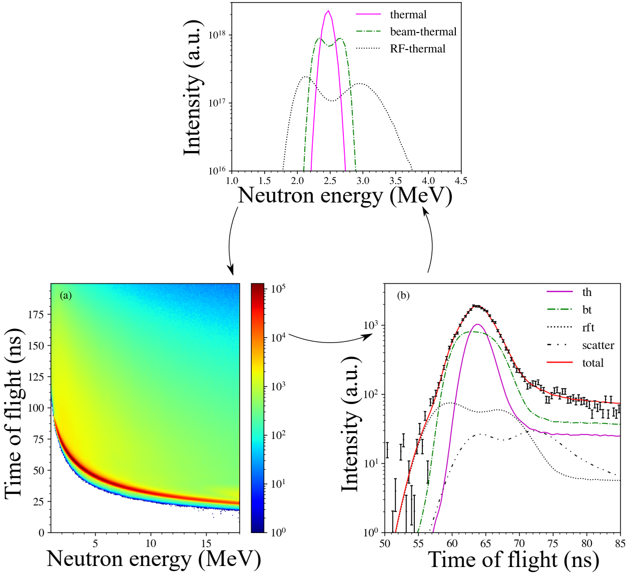
Fitting model to TOF spectrum

Fitting procedure

- Model neutron energy distribution
- Fold with detector response function
- Fit to data
- Tweak model parameters

Detector response function

- TOFOR model in Geant4
- Geometric effects
- Reaction cross section libraries
- Energy dependent detection efficiency
- Light transport to PMTs



Measurements of the ^{5}He resonance in T(T,2n)α

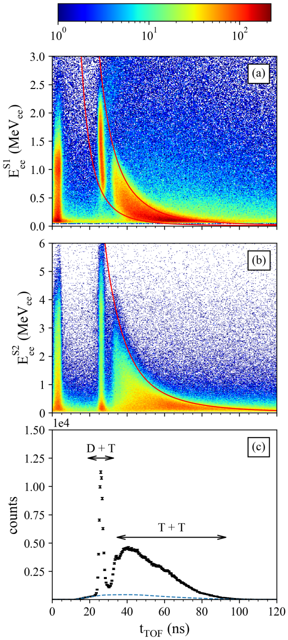
Measurements of the ^{5}He resonance

Experiments at JET with T plasmas

- $n_\mathrm{T}/(n_\mathrm{T}+n_\mathrm{D}) \sim 99\%$
- Effective CM energy at 45 keV

Three-body reaction T + T $\longrightarrow \alpha$ + 2n

- Broad continuum of neutron energies
- $0 < E_\mathrm{n} < 9.5$ MeV



Measurements of the ^{5}He resonance

Experiments at JET with T plasmas

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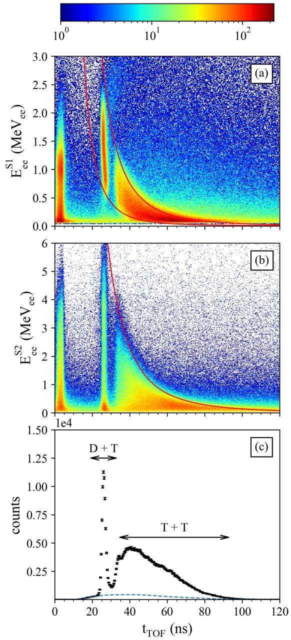
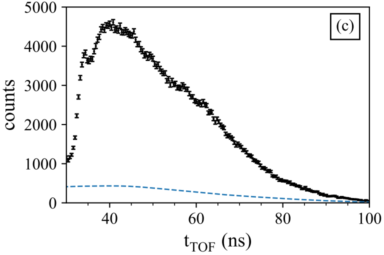


Intermediate reactions

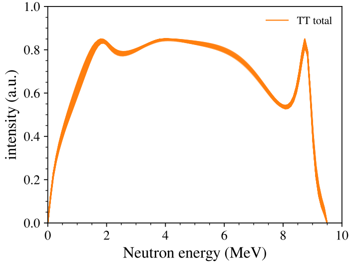
- $T + T \rightarrow {}^5He + n$
- ${}^5He \rightarrow \alpha + n$
- Introduces structure in the TT neutron energy spectrum



Modelling the TT neutron spectrum

C. Brune (Ohio University) R-matrix model

- particle emissions as sequential 2-body decays
- considers transitions from the T+T state
- partial waves
  - e.g. transition to ^{5}He + n or ^{5}He* + n
- interference between partial waves



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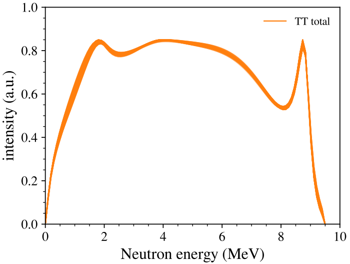
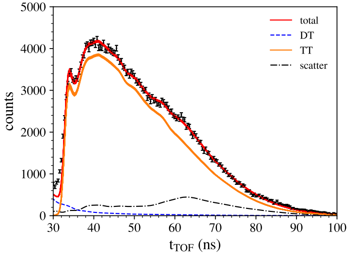
Model parameters

- 6 free parameters
- partial wave intensities





Conclusions and outlook

Conclusions and outlook

Determined the TT neutron energy distribution

- TOFOR data
- JET discharges at centre-of-momentum $E_{\mathrm{CM}} = 45$ keV

Compare with National Ignition Facility (NIF)

- TT from inertial confinement
- E_{CM} 16-50 keV

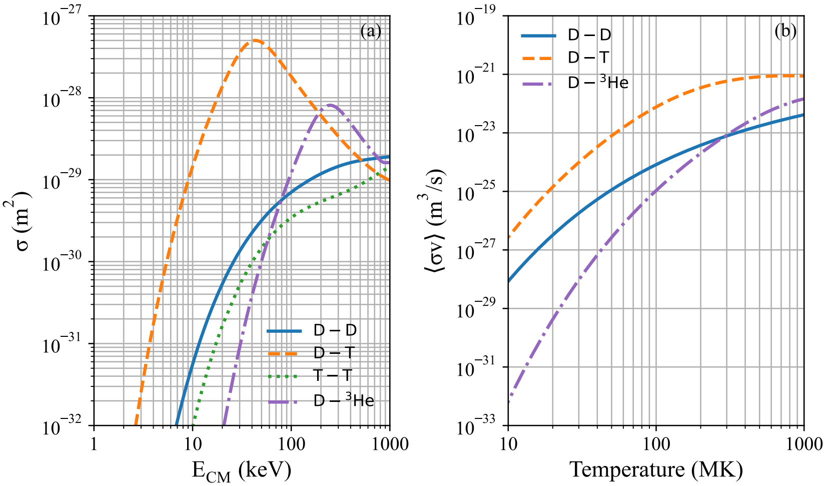
Examine spectral shape

- Energy-dependency
- Especially in peak from ^{5}He + n

Thank you for your attention, questions?

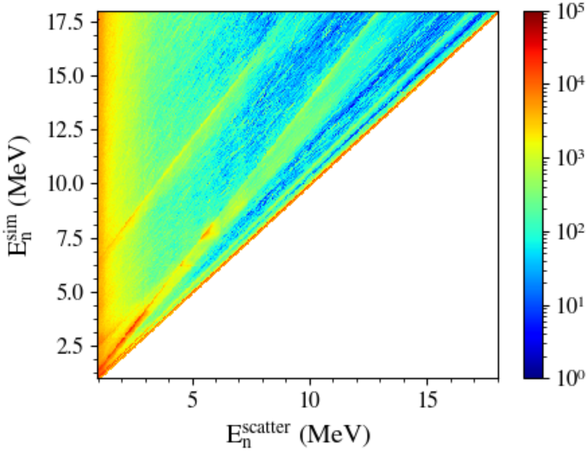
Backup slides

Reactivity



(a)
D − D
D − T
T − T
D − ³He
σ (m²)
E_CM (keV)
1
10
100
1000
10^−27
10^−28
10^−29
10^−30
10^−31
10^−32
(b)
D − D
D − T
D − ³He
⟨σv⟩ (m³/s)
Temperature (MK)
10
100
1000
10^−19
10^−21
10^−23
10^−25
10^−27
10^−29
10^−31
10^−33

Backscatter matrix



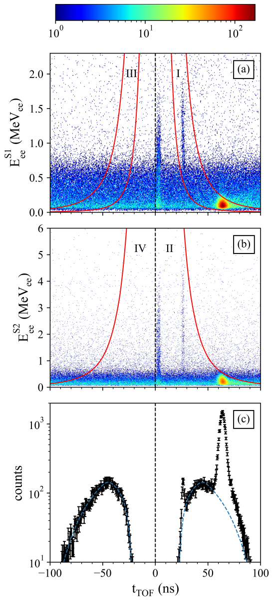
Fokker-Planck

Fokker-Planck equation

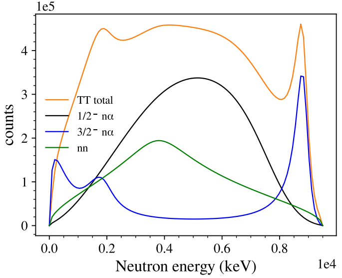
$$\frac{\partial f}{\partial t} = \frac{1}{v_{\mathrm{i}}^2}\frac{\partial}{\partial v_{\mathrm{i}}}\left[-\alpha v_{\mathrm{i}}^2 f + \frac{1}{2}\frac{\partial}{\partial v_{\mathrm{i}}}\left(\beta v_{\mathrm{i}}^2 f\right) + \frac{1}{2} D_{\mathrm{RF}} v_{\mathrm{i}}^2 \frac{\partial f}{\partial v_{\mathrm{i}}}\right]$$
$$+ S\left(v_{\mathrm{i}}\right) + L\left(v_{\mathrm{i}}\right).$$

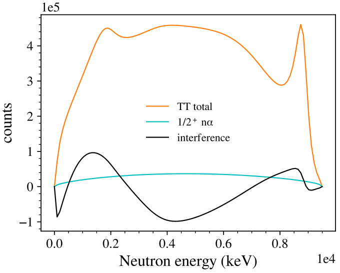
- α, β Spitzer coefficients
- D_{RF} ICRH diffusion coefficient
- S, L source and loss terms

Kinematic cuts + background subtraction

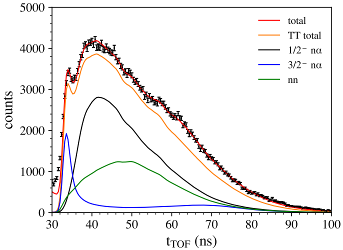


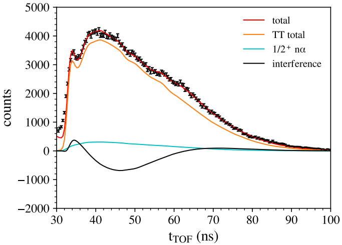
Energy distributions

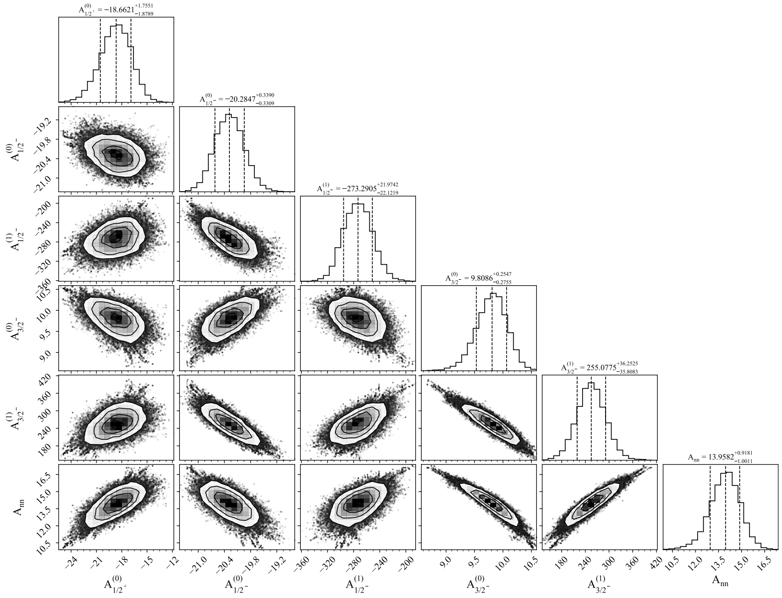




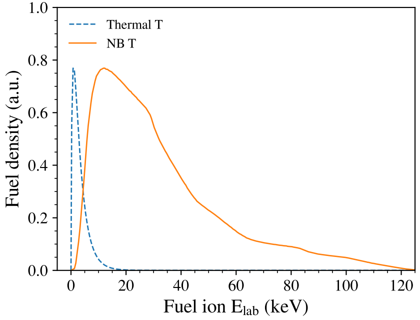
Fit to TOF spectrum

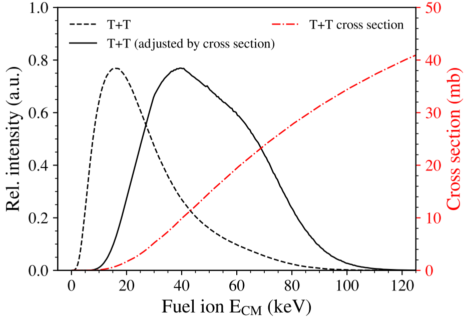





$A^{(0)}_{1/2^+} = -18.6621^{+1.7551}_{-1.8789}$
$A^{(0)}_{1/2^-} = -20.2847^{+0.3390}_{-0.3309}$
$A^{(1)}_{1/2^-} = -273.2905^{+21.9742}_{-22.1219}$
$A^{(0)}_{3/2^-} = 9.8086^{+0.2547}_{-0.2755}$
$A^{(1)}_{3/2^-} = 255.0775^{+36.2525}_{-35.8083}$
$A_{nn} = 13.9582^{+0.9181}_{-1.0011}$
$A^{(0)}_{1/2^+}$
$A^{(0)}_{1/2^-}$
$A^{(1)}_{1/2^-}$
$A^{(0)}_{3/2^-}$
$A^{(1)}_{3/2^-}$
A_{nn}

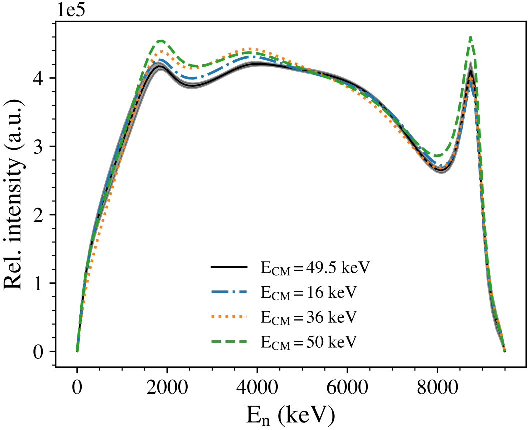
CM energy distribution

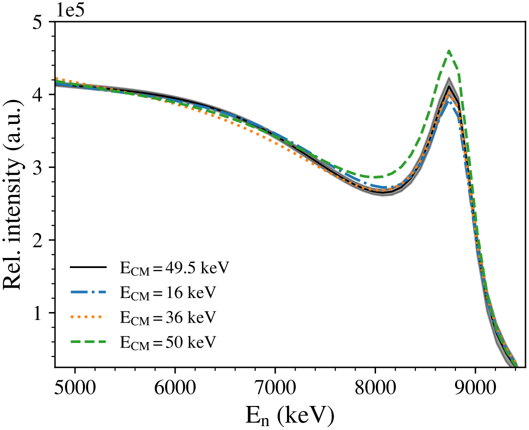




E_{CM} = 49.5 keV with a standard deviation of 18 keV.

Comparison to NIF





Background reduction (kinematic cuts)

In S1 detectors (top panels)

- min/max scattering angle $\theta_{\text{max}}, \theta_{\text{min}}$
- upper/lower E limit for t_{TOF}

In S2 detectors (middle panels)

- no scattering angle limit, but...
- upper E limit from S1 interaction

TOF projection (bottom panels)

- with/without kinematic cuts
- ~400% improvement of DT peak S/B ratio