Measurement of neutron-induced enhancement of the triple-alpha process with a Time Projection Chamber

Jack Bishop



# Measurement of neutron-induced enhancement of the triple-alpha process with a Time Projection Chamber


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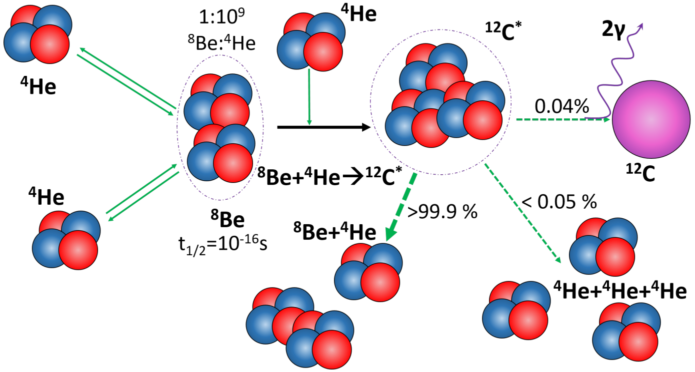
# Overview

# Triple-alpha process

# Triple-alpha process - Hoyle state



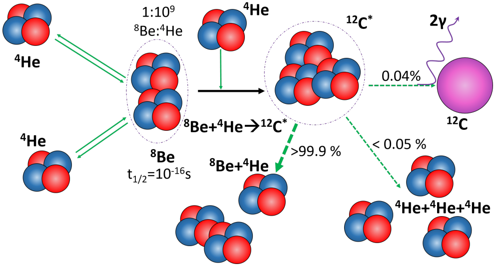
- Triple-alpha process overcomes the A=5, 8 mass gap - fusing three $\alpha$-particles into carbon-12
- Presence of resonance at 7.65 MeV in carbon-12 enhances reaction rate by seven orders of magnitude - the Hoyle state!



# Reaction rate

- Reaction rate given by:

$$R \propto \frac{\Gamma_\alpha \Gamma_{rad}}{\Gamma} T^{-3/2} \exp\left(-\frac{Q}{kT}\right) \xrightarrow{\Gamma_\alpha \approx \Gamma} \Gamma_{rad} T^{-3/2} \exp\left(-\frac{Q}{kT}\right) \quad (1)$$



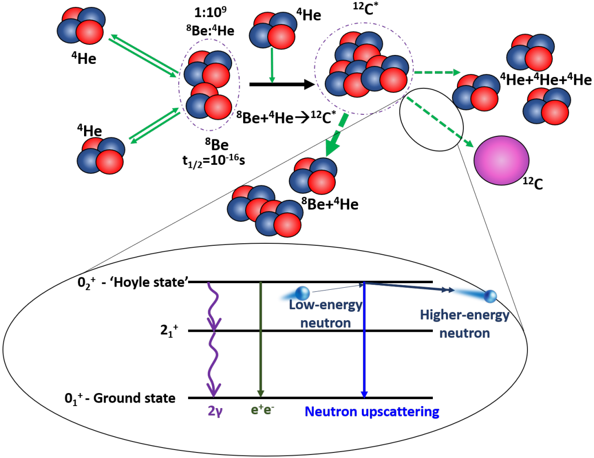

- $\Gamma_\alpha = 9.3$ eV
- $\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi = 38$ meV
- $\Gamma_\gamma \approx 60\Gamma_\pi$

# Neutron upscattering

# Neutron upscattering



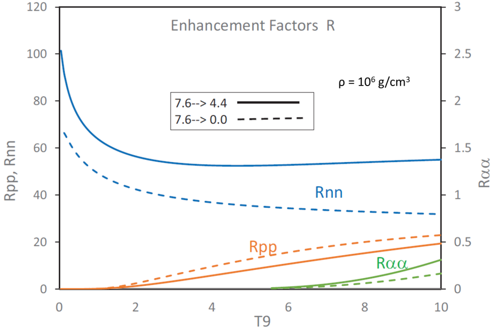
- Additional 'radiative' decay mechanisms available! Particle-induced upscattering



# Enhancements from neutron/proton upscattering



[M. Beard et al. Phys. Rev. Lett. 119, 112701]



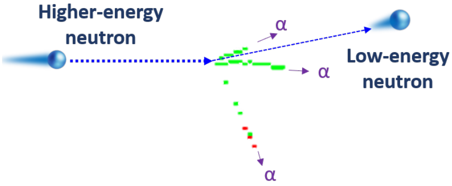

High-density environment, large neutron enhancements at low temperature ($\approx 0.2$ GK)

Neutrino wind following a supernova explosion/in an x-ray burster

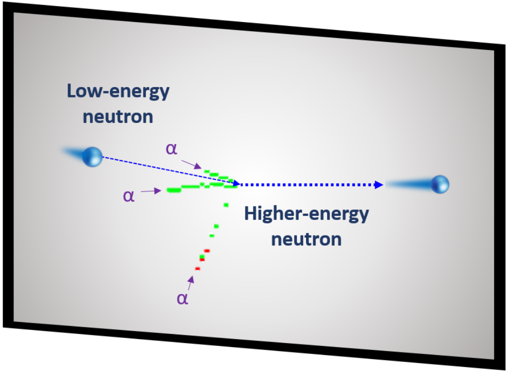
# Time-reversal symmetry



**Experimental case**




**Time-reversed astrophysical case**



# Enhancements from neutron/proton upscattering



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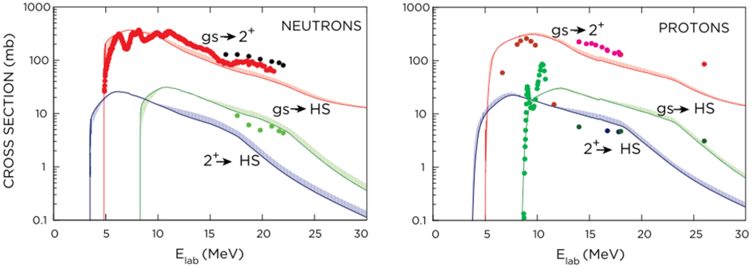



- Resonances in proton inelastic channel, large effect on XS if neutron resonances also present
- No data on gs → HS from 8 to 16 MeV, higher E data deviate from HF OMP predictions
- $\Gamma_{rad} = \Gamma_\gamma + \Gamma_\pi + \Gamma_{n_{20}} + \Gamma_{p_{20}} + \Gamma_{n_{21}} + \Gamma_{p_{21}}$

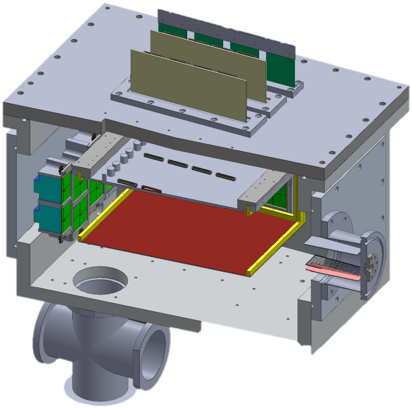
# TexAT TPC

# TexAT overview



TexAT TPC - TEXas Active Target Time Projection Chamber

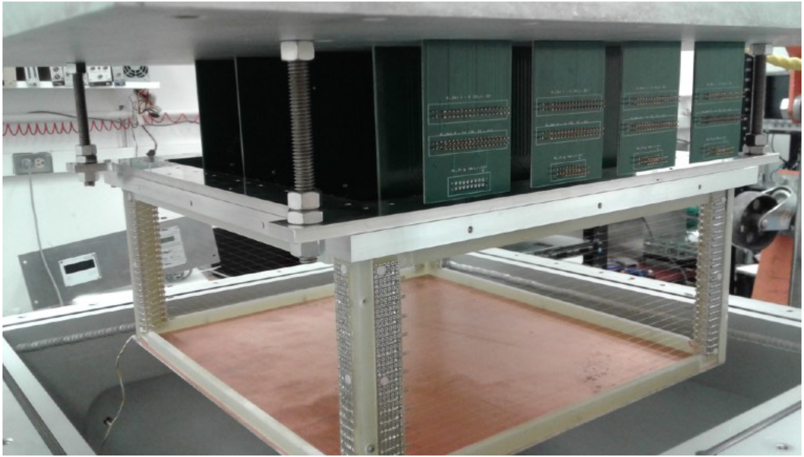
- 224 x 240 x 130 mm sensitive area
- Segmented readout using Micromegas, 1024 channels, pos. res. $\approx$ 1.5 mm in beam direction
- Gas Electron Multipliers (GEMs) provide additional gain. Low dE/dx particle tracks possible
- General Electronics for TPCs (GET) system digitizes waveforms. 512 time buckets at 10 MHz
- Ancillary Si+CsI telescope wall



NIM paper: E. Koshchiy et al. - NIMA 957, 163398 (2020)

# TexAT overview

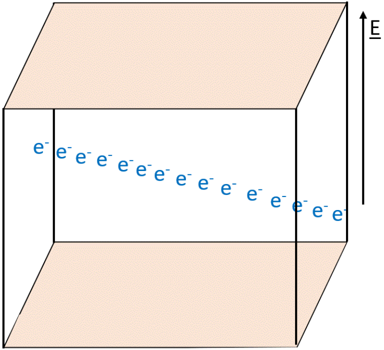




# How a TPC works

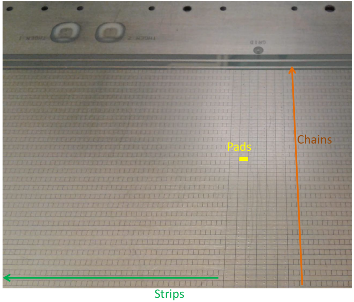


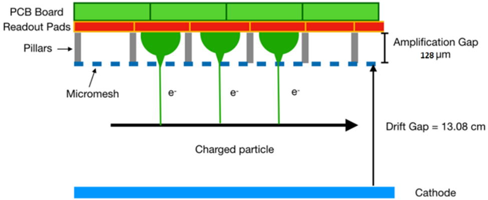




# Micromegas

- Micromegas-based readout
- Amplify and measure electron drift signals
- 128 $\mu$m gap
- Central region pads 1.75 x 3.5 mm
- Side regions require multiplexing into 'strips' and 'chains' parallel and perpendicular to beamline
- THGEMs (1.25 mm thick) or GEMs (128 $\mu$m thick)



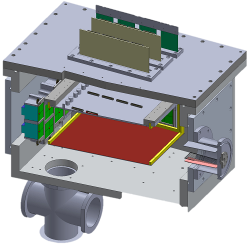
# Neutron-induced measurements

# Neutron-induced measurements with TexAT

TPCs can be well-suited to many different types of neutron-induced measurements

Active-target TPC filled with $CO_2$ looking to measure:

- $^{12}\mathrm{C}(n, n_2)3\alpha$ - inelastic neutron scattering to the Hoyle state
- $(^{16}\mathrm{O}(n, \alpha)^{13}\mathrm{C}$ run parasitically)

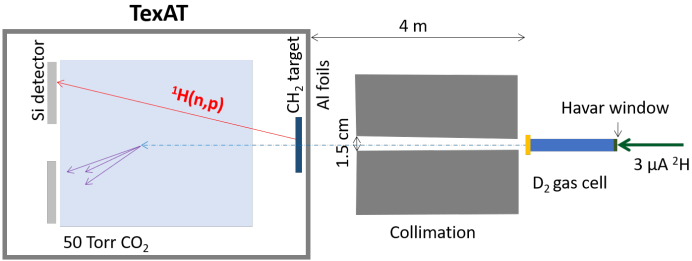


These two measurements can be measured with the same experimental setup - TexAT with 50/100 Torr $CO_2$ gas. Represents a great opportunity for future measurements with low-energy recoil products - can be well resolved using low pressure TPC.

# Experimental setup



- Edwards Accelerator Lab - Ohio University
- 50/100 Torr $CO_2$
- Neutron beam from d(d,n) reaction - scanning from 7.2-10.0 MeV
- $0.5 \times 10^4$ neutrons/s: $\sigma(E_n) \approx 200$ keV
- Normalization is a big issue!



# Normalization





Total normalization is very important. Relying on a few different techniques:

- Total integrated beam current - $0^\circ$ cross section known very well for d(d,n)
- Measurement of $^{12}\mathrm{C}(n, n_0)$ and $^{16}\mathrm{O}(n, n_0)$ inside TexAT
- Measurement of $^{1}\mathrm{H}(n, p)$ cross section using a silicon detector inside TexAT at $\sim 10^\circ$ from a thin $CH_2$ foil
- NE213 placed directly behind TexAT
- Normalization with $^{12}\mathrm{C}(n, \alpha)$ and $^{16}\mathrm{O}(n, \alpha)$

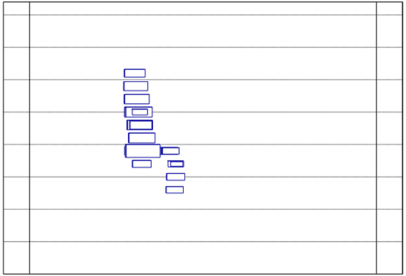
# Current status





'Difficult' experimental campaign - COVID19 delays mid-experiment

Plenty of beautiful Hoyle events! Reconstructed and separated - **big image recognition problem!**



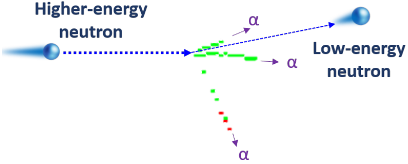
Appropriate selections need to be placed and the total counts accumulated → cross section

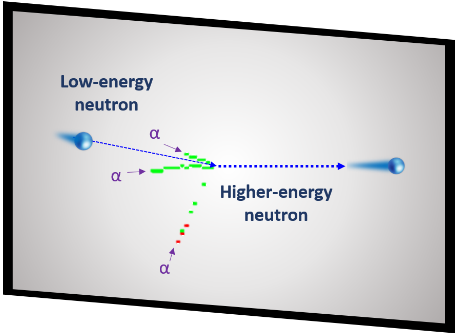
# Press Coverage



## Scientific American Article: March 19, 2020

Carbon Conundrum: Experiment Aims to Re-create Synthesis of Key Element



# Conclusion

# Conclusions



- TexAT - general purpose TPC capable of measuring different reaction mechanisms
- Study the role of neutron inelastic scattering to the Hoyle state
- Cross section of this reaction informs us about time-reversed astrophysical case
- Enhances the triple-alpha reaction rate
- *'Might the enhanced rates produce sufficient seeds in the neutrino driven wind of a core-collapse supernovae to make a successful r process less likely?'*
- First instance of neutron-induced measurements with a TPC
- Results coming soon*!

*Terms and conditions apply

# Collaborators





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