Almost Medium-Free Measurement of the Hoyle State Direct-Decay Component With a TPC

Jack Bishop
Postdoctoral Research Associate
Cyclotron Institute
Texas A&M University

Previews of the Future in Low-Energy Experimental Nuclear Physics
National Postdoctoral Seminar Series

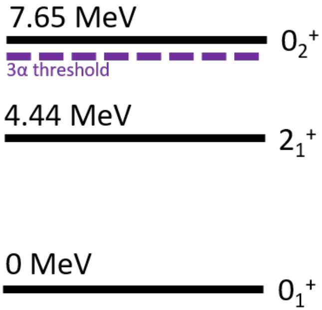
February 18$^{\mathrm{th}}$ 2021

Contents

The Hoyle state

CYCLOTRON INSTITUTE

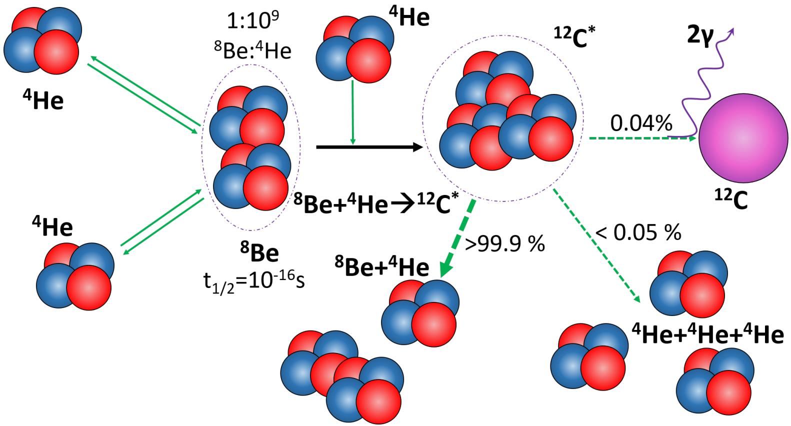
Hoyle state



Hoyle state:

- Second-excited state in ^{12}C
- Sits just above α-threshold
- Vitally important for the triple-alpha process

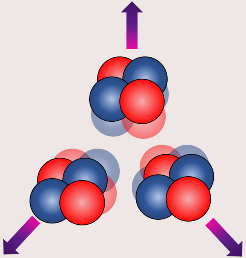
Triple alpha process



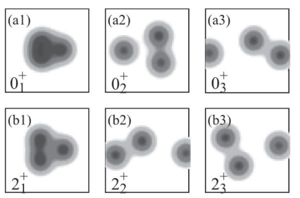
Hoyle state enhances triple alpha process by seven orders of magnitude!

Why do we care?!

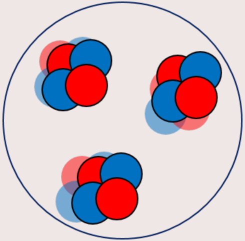
Internal structure of the Hoyle state has an impact on this branching ratio $\rightarrow$ How do we think about the structure of the Hoyle state? Highly 3α clustered - yes, but how so?



Breathing mode of triangular arrangement of α-particles (D_{3h} symmetry [1])?



More general 'bent-arm' ^{8}Be + α structure (from AMD calculations [2])?



Dilute gas of α-particles [3]?

[1] D. J. Marín-Lambárri et al. Phys. Rev. Lett. 113, 012502 (2014)
[2] Y. Kanada-En'yo Prog. Theor. Phys. 117, 4 (2007)
[3] Tohsaki, Horiuchi, Schuck and Röpke, Phys. Rev. Lett. 87, 192501 (2001)

Alpha-particle condensates

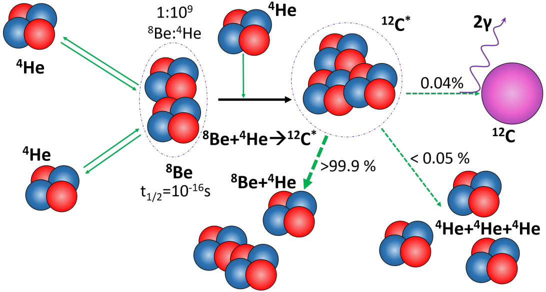
- Transition from a fermionic to bosonic system
- Large occupation of 0s orbital
- Different phase of nuclear matter where the density drops below $\sim \frac{\rho_0}{4}$
- Experimental evidence so far inconclusive $[1-3]$ - Hoyle state only well-studied candidate state
- Decays to other α-condensates should be enhanced [4]
- For $^{16}\mathrm{O}, ^{20}\mathrm{Ne}, \ldots$ Coulomb barrier suppresses these signature decays

Dilute gas of α-particles: α-condensate would have an enhanced direct 3α decay

[1] J.A. Schwartz et al. Phys. Rev. C 91, 034317 (2015)
[2] M. Barbui et al. Phys. Rev. C 98, 044601 (2018)
[3] JB et al. Phys. Rev. C 100, 034320 (2019)
[4] Tz. Kokalova et al. Phys. Rev. Lett. 96, 192502 (2006)

Hoyle decays

Aim of this measurement to measure Hoyle decay branching ratio directly to 3α rather than via $^{8}\mathrm{Be(g.s)}$



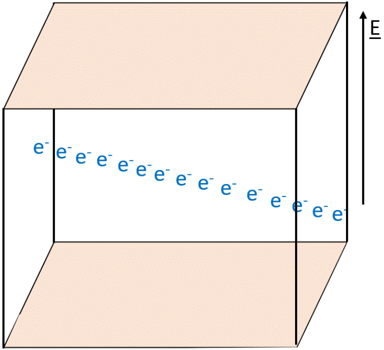
Current limits <0.019% 95% C.L. [1-3].

Factor of 10 or more improvement needed for model rejection [4], i.e. 1 in 40,000.

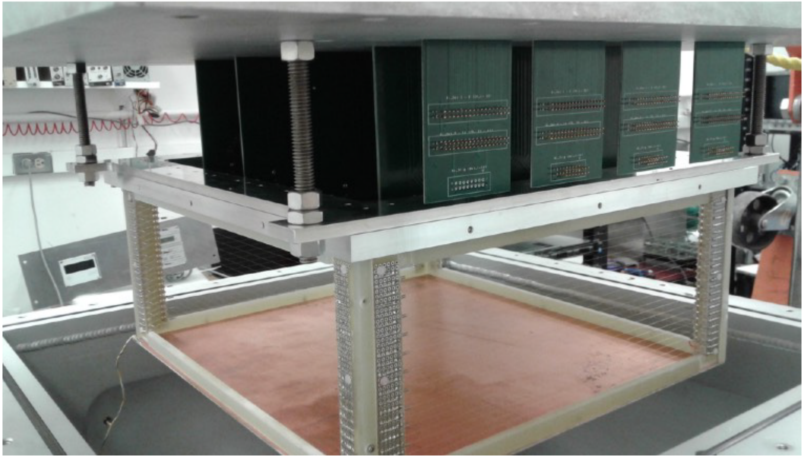
[1] R. Smith et al., PRL **119**, 132502 (2017)
[2] D. Dell'Aquila et al., PRL **119**, 132501 (2017)
[3] T.K. Rana et al., Phys. Lett. B, 793 130-133 (2019)
[4] H. Zheng et al., PLB **779** 460-3 (2018)

TexAT TPC

How a TPC works

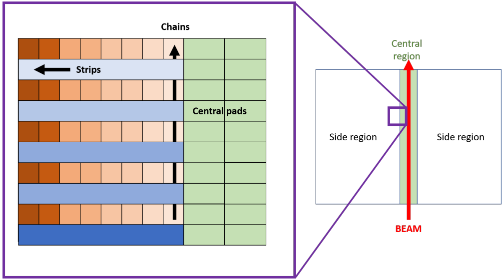


TexAT overview



Micromegas

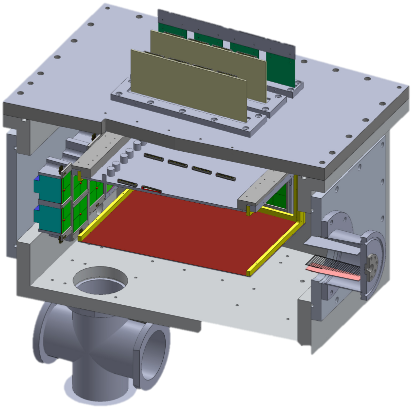
- Micromegas-based readout
- Amplify and measure electron drift signals
- 128-μm gap
- Central region pads 1.75 x 3.5 mm
- Side regions require multiplexing into 'strips' and 'chains' parallel and perpendicular to beamline
  - Future TeBAT upgrade eliminates this necessity
- THGEMs (1.25-mm thick) provide additional gain factor of 10-100



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 (not used in this work)



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

Past experiments

Nuclear structure/exotic nuclei

- $^{8}\mathrm{B}(p,p)$
  - J. Hooker et al. Phys. Rev. C 100, 054618 (2019)
- $^{10}\mathrm{C}/^{14}\mathrm{O}(\alpha,\alpha)$
- $^{12}\mathrm{Be}(p,p)$
- $^{9}\mathrm{Li}(p,p)$

Direct fusion measurement

- $^{8}\mathrm{B}+^{40}\mathrm{Ar}$
  - Under review PLB

Transfer reactions

- $^{12}\mathrm{B}(d,^{3}\mathrm{He})$
- $^{1}\mathrm{H}(^{6}\mathrm{He},t^{\star})$

β-delayed particle decay

- $(^{12}\mathrm{N},\beta 3\alpha)$
  - JB et al., NIMA 964, 163773 (2020)
  - JB et al., PRC 102, 041303(R) (2020)
  - JB et al., Under review PRL

Neutron-induced measurements

- $^{12}\mathrm{C}(n,n_2)3\alpha$ and $^{16}\mathrm{O}(n,\alpha)$

β-delayed particle decay

Experimental details

Performed Sep 2018/Mar 2019

Using TexAT, can measure both the implant and decay of a radioactive nucleus **'one at a time'** at Cyclotron Institute, Texas A&M.

- Beam of ^{12}N from ^{3}He(^{10}B, ^{12}N)n using MARS + K500
- Slowed down by aluminum degrader to 25 MeV entering chamber
- Stop further implantations
- Completely stopped by 20 Torr CO_2 gas
- Implant and then subsequent decay ($t_{1/2}$ = 11.0 ms) tracks recorded by TPC
- Ready for further events
- Sensitive to $^{12}C^\star \rightarrow 3\alpha$; total BR $\approx$ 2%
- Want to measure this direct 3α BR

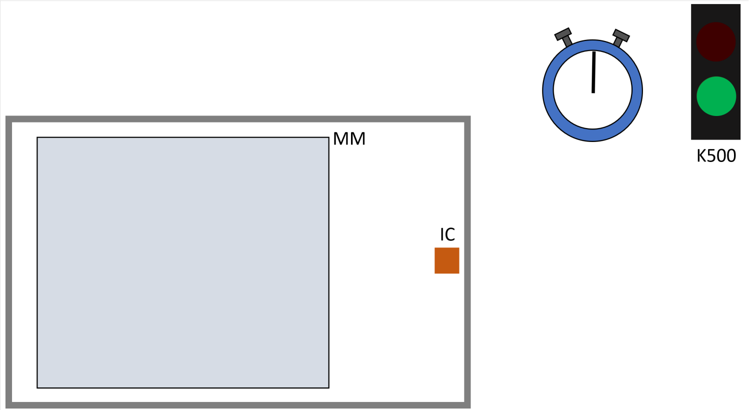
JB et al., NIMA 964, 163773 (2020)

GET 2p-mode

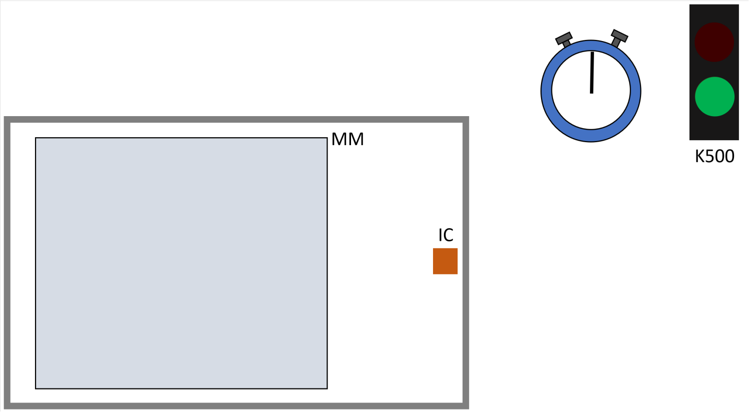
GET system allows for 2 half-triggers.

- First trigger, L1A. Second trigger, L1B
- L1B required within 30 ms of L1A or else ‘half-event’ written to disk
- L1A implant then if 2% which decay to 3α then can correlate these events
- After 30 ms or L1B, beam can be sent back into TexAT

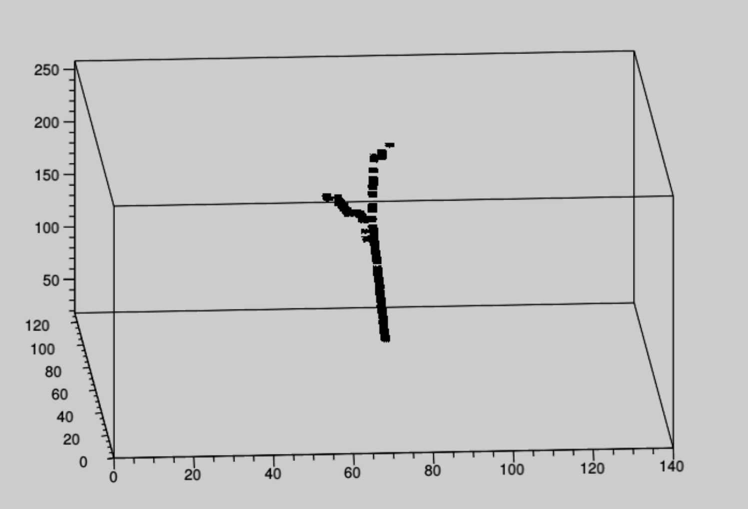
α-bound population



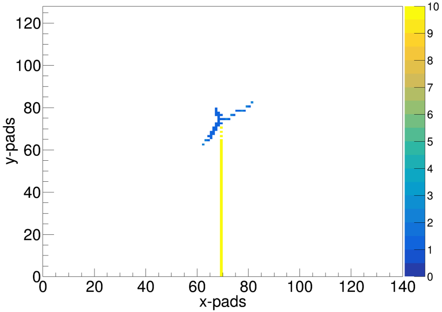
α-unbound population

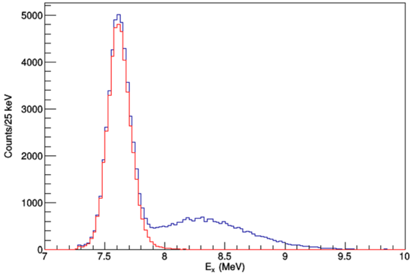


Track reconstruction



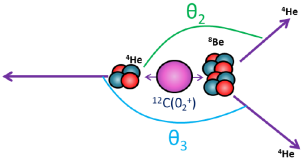
Selecting Hoyle decays



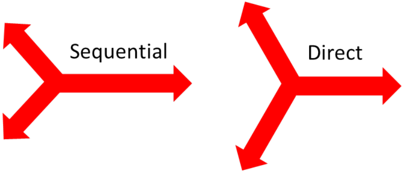


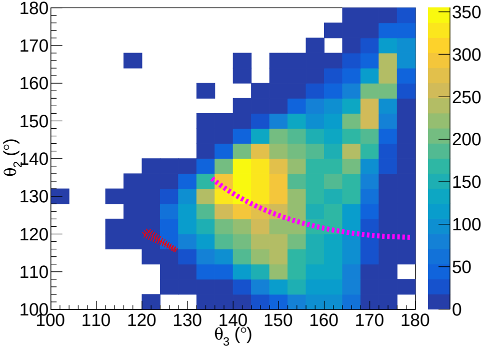
- Correlate implant location to decay vertex
- Hoyle decays are selected by the energy from the decay
- Escaping events excluded

Differentiating Hoyle decays breakup mode



Measuring the angle of the decay arms gives signature of direct decay.
'Y' shape vs. equilength shape



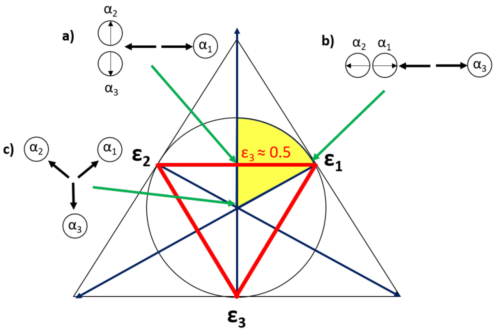


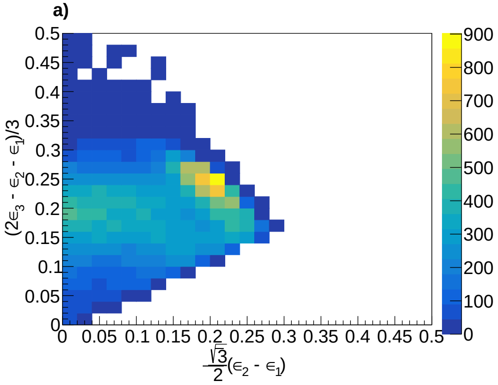
Experimental data vs sequential locus (magenta) and direct locus (red)

Differentiating Hoyle decays breakup mode

Looking at energy partition of final-state α-particles

Dalitz plot





Results

Formulate χ^2 for sequential and direct from θ_{23} and Dalitz plot for each event.

$$\chi^2_\theta = \frac{\min\{(\theta_2 - \theta_{2_{\text{theory}}})^2 + (\theta_3 - \theta_{3_{\text{theory}}})^2\}}{\sigma^2_\theta},$$

$$\chi^2_D = \begin{cases} (\frac{y - y_{\text{seq}}}{\sigma_D})^2, & \text{for sequential} \\ (\frac{x^2+y^2}{\sigma^2_D}), & \text{for direct} \end{cases}$$

Extract p-value (p_χ) for sequential and direct

Likelihood formulation:

$$P_{seq} = p_{\chi_{seq}}(1-\delta),$$

$$P_{dir} = p_{\chi_{dir}}\delta,$$

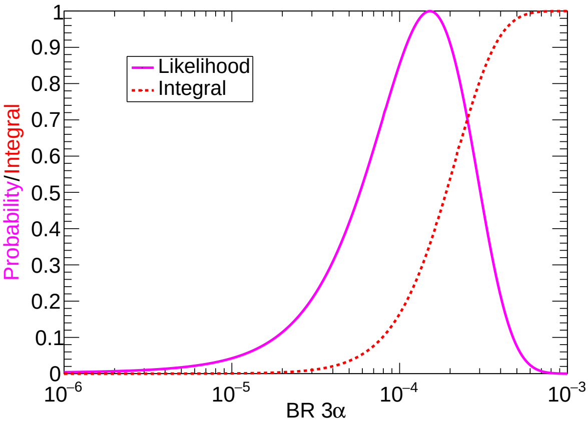
where δ is the 3α branching ratio.

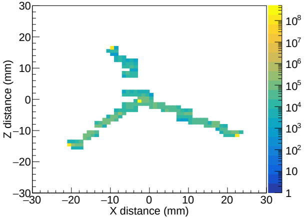
$$\mathcal{L}(\delta) = \sum_n \log(p_{\chi_{seq}}(1-\delta) + p_{\chi_{dir}}\delta),$$

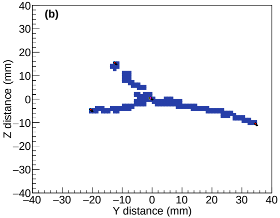
Results

95% C.L.: $0.0058\% < BR < 0.043\%$, Most-likely BR $\sim 0.01\%$

For the first time, have demonstrated sensitivity to the direct-decay component







CYCLOTRON INSTITUTE

Conclusion

Direct 3α BR of 0.01% $\rightarrow$ what does this imply about an α-condensate?

Complications:

- Contributions from the 'ghost peak' in $^{8}\mathrm{Be}$ $\rightarrow$ 0.01% $=$ actual direct 3α $+$ ghost peak
- Final-state Coulomb interactions $+$ identical boson symmetrization effects

Predictions for direct 3α BR:

- WKB phase-space prediction: 0.18 % [1]
- R-Matrix $+$ FSCI: 0.0017% $\rightarrow$ 1.1% [2]
- Faddeev: 0.014 % $\rightarrow$ 0.05% [3]
- Exp: From 2_2^+ state in $^{12}\mathrm{C}$: 0.00057%[4]

Exhausted the experimental limits of this study - more theory needed

[1] R. Smith, JB et al., Few-Body Systems 61, 14 (2020)
[2] J. Refsgaard et al. J. Refsgaard et al., Phys. Lett. B 779, 414 (2018)
[3] S. Ishikawa. Phys. Rev. C 90 061604 (2014)
[4] R. Smith et al., Phys. Rev. C 101 021302(R) (2020)

Collaborators

J. Bishop, **G.V. Rogachev**, E. Koshchiy, S. Ahn, B.T. Roeder, A. Saastamoinen, E. Aboud, A. Bosh, M. Barbui, C. Hunt, J. Hooker, H. Jayatissa, R. O'Dwyer, S. Upadhyayula
Cyclotron Institute, Texas A&M University, College Station, USA
L.G. Sobotka, C. Pruitt
Department of Chemistry, Washington University, St. Louis, USA
S.T. Marley, R. Malecek
Department of Physics and Astronomy, Louisiana State University, USA
E. Pollacco
IRFU, CEA Saclay, Gif-sur-Yvette, France

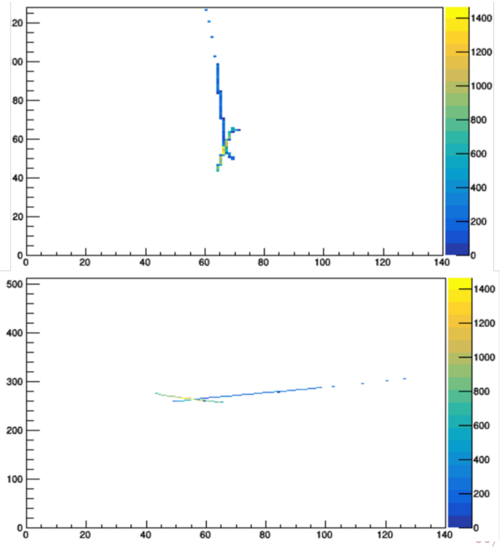
Project funding

This material is based upon work supported by the Department of Energy under award no. DE-FG02-93ER40773 and by the National Nuclear Security Administration through the Center for Excellence in Nuclear Training and University Based Research (CENTAUR) under grant number DE-NA0003841.

Future projects

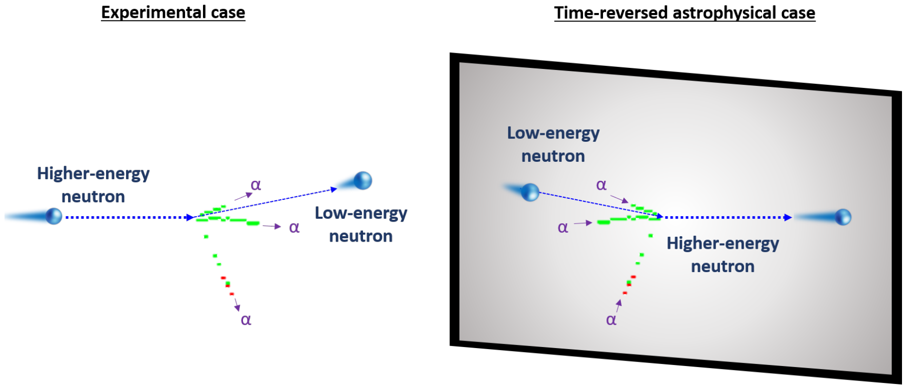
Studies of $^{13}\mathrm{N}$

- Extending β-delayed charged-particle technique to study $^{13}\mathrm{N}$
- $\alpha + \alpha + \alpha + p$
- States populated decay to both $^{9}\mathrm{B}^{\star}$ and $^{12}\mathrm{C}^{\star}$



Scientific American Article: March 19, 2020

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



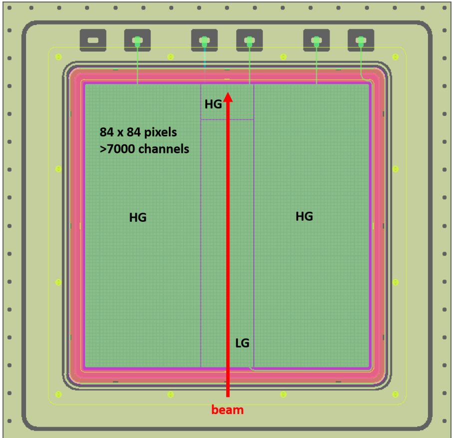
Studying $^{12}\mathrm{C}(n, n_2)3\alpha$ with TexAT at Ohio University, Edwards Laboratory

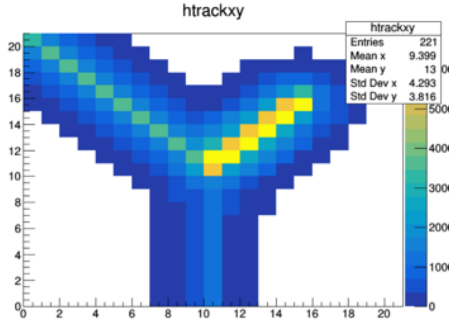
Exciting experimental results coming soon*! Watch this space *Terms and conditions apply

TeBAT

Upgrade to TexAT as collaboration between Cyclotron Institute and University of Birmingham, UK

Moving to resistive Micromegas design





Deliberate dispersion of charge $\rightarrow$ position resolution down to $\sim$ 200 μm

Conclusion

Conclusions

TexAT - general purpose TPC capable of measuring different reaction mechanisms

Beta-delayed charged-particle decay in a TPC allows for extremely high-sensitivity measurements of few-body decays

Sensitivity to direct-decay component demonstrated for the first time for the Hoyle state

More theory input is needed but no evidence to support postulate that Hoyle state is an α-condensate

Branching ratios from $^{12}\mathrm{N}$

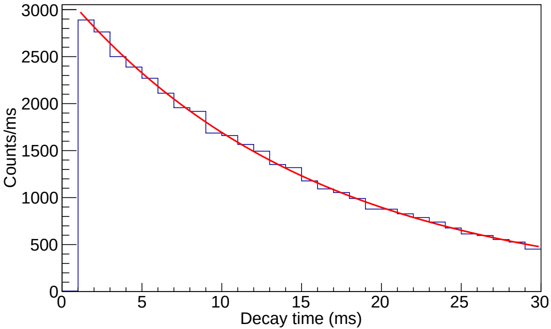
40,000 Hoyle decays that safely stop inside Micromegas
Each $^{12}\mathrm{N}$ measured with Micromegas and ion counter scalar
Branching ratios extracted in comparison to KVI result - S. Hyldegaard (PLB **678** 459–464 (2009))

Table: Branching ratios for states in $^{12}\mathrm{N}$ in this work against those from KVI.

State	KVI(%)	Current work(%)
7.65 MeV - 0_2^+	1.44 ± 0.03	1.58 ± 0.01 (stat.) ± 0.11 (sys.)
7.3-16.3 MeV - 3α	2.11 ± 0.03	2.54 ± 0.01 (stat.) ± 0.18 (sys.)
$0_2^+/3\alpha$	68 ± 2	62.1 ± 0.4 (stat.) ± 0.2 (sys.)

Decay time of ^{12}N

From time between L1A and L1B trigger (implant of ^{12}N) and decay (3α) - get decay time

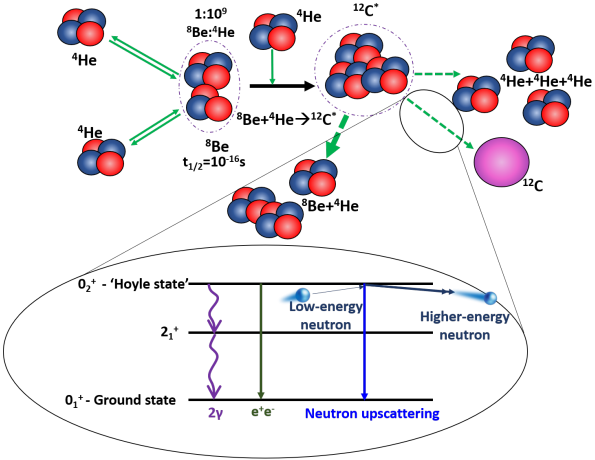


Literature:
$t_{1/2} = 11.000 \pm 0.016$ ms
Agrees well with literature with **no background** terms included showing cleanliness of selection.

TexAT:
$t_{1/2} = 10.92 \pm 0.11$ (stat.) $\pm$ 0.01 (sys.) ms

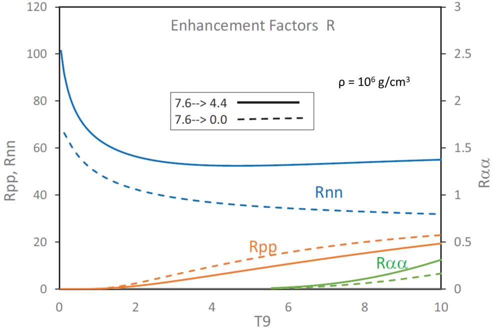
Neutron upscattering

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



Enhancements from neutron/proton upscattering

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

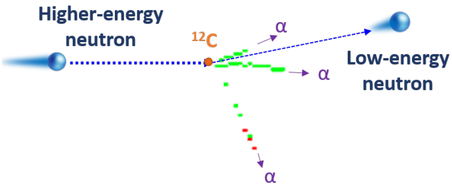


High-density environment, large neutron enhancements at low temperature ($\approx$ 0.2 GK)

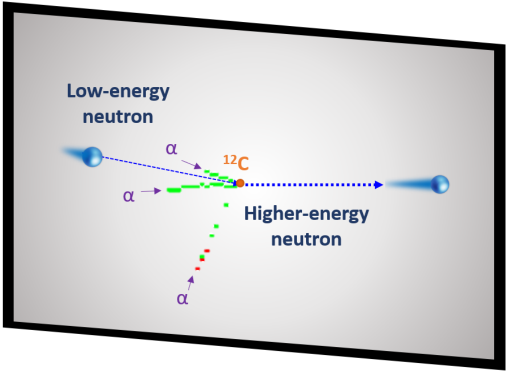
Neutrino wind following a supernova explosion/in an x-ray burster

Time-reversal symmetry

Experimental case

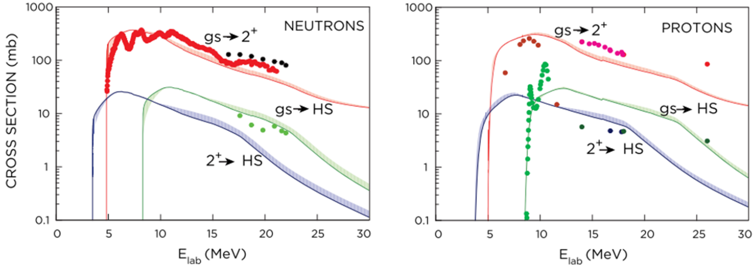


Time-reversed astrophysical case



Enhancements from neutron/proton upscattering

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



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