Measurement of $^{16}\mathrm{C} + {}^{12,13}\mathrm{C}$ Fusion with Implications for X-ray Superbursts

Valarie Milton

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Louisiana State University
Department of Physics & Astronomy

Astrophysical Motivation

- X-ray Superbursts
  - Similarly to Type I X-ray bursts (XRB's), occur in a binary system with a neutron star accreting matter from the companion star
  - Superbursts have a different underlying mechanism compared to Type I X-ray bursts

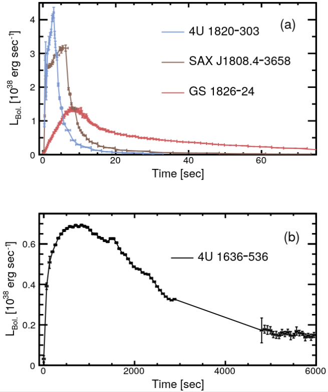


Figure 1: *Meisel et al. 2018*

Astrophysical Motivation

- The superbursts are driven by the burning of ashes from Type I XRB's (C, O, Ne, Si and heavier elements at high densities) (*V. Singh et al 2019*)
- The pycnonuclear burning of neutron rich nuclei is most likely the source of their internal heat

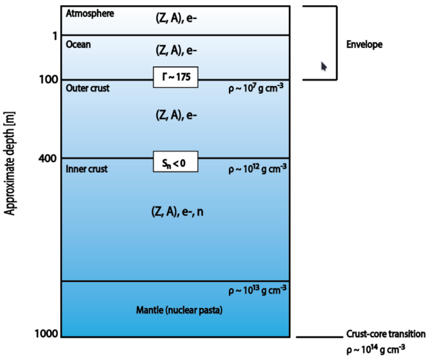
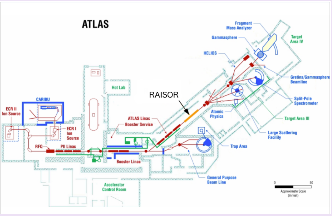


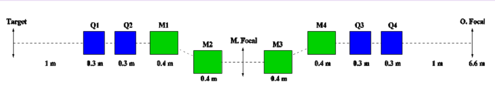
Figure 2: Meisel *et al.* 2018

Neutron-rich carbon fusion is one factor that can be measured to constrain superburst models!

Experimental Overview

- Measurement of ^{16}C + ^{12,13}C fusion
- Argonne National Laboratory (ANL) using the Argonne Tandem LINAC Accelerator System (ATLAS)
- ^{16}C radioactive ion beam was produced using the RAdioactive Ion SeparatOR (RAISOR) at 220 MeV with a rate of 1,200 pps and a purity of 50-80%





Experimental Overview

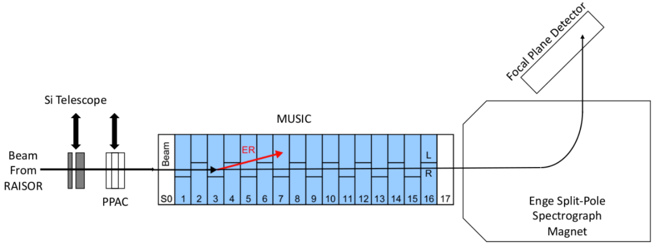


Figure 3: *A. Hood PhD Thesis 2019*

- Silicon telescope measured the beam composition ($\Delta E - E$)
- Parallel-Plate Avalanche Counter (PPAC) used for time-of-flight information
- Split-Pole Spectrograph (SPS) measured the beam energy
- An aluminum degrader (0.36 mm) was placed behind the entrance window to decrease the beam energy

MUlti-Sampling Ionization Chamber (MUSIC)

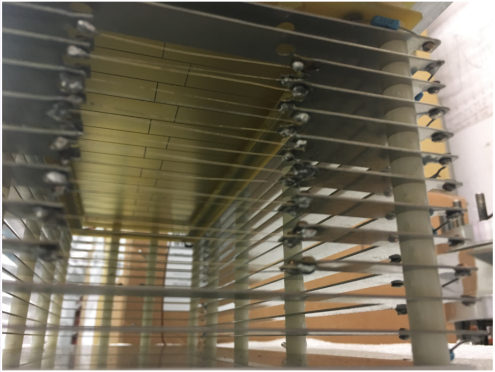


Figure 4: *A. Hood PhD Thesis 2019*

- Gas filled ionization chamber that functions as an active-target detector
- Filled with methane (or ^{13}C-enriched methane) at 400 Torr and 293 K

MUlti-Sampling Ionization Chamber (MUSIC)

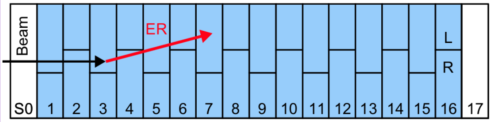


Figure 5: *Carnelli et al. 2015*

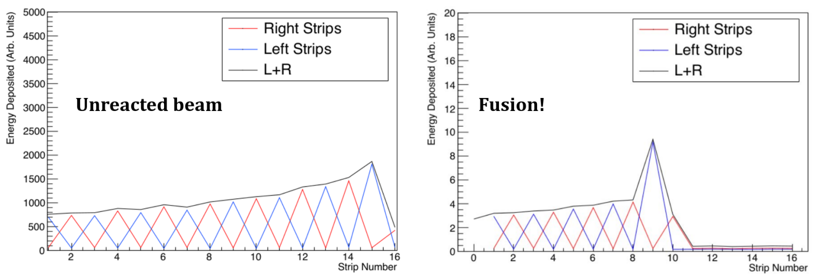


Figure 6: *A. Hood PhD Thesis 2019*

Analysis: Identifying Fusion Events

Fusion Criteria:

- Unreacted prior to fusion
  - $p_{-1} < 0.2$
- A sharp peak within 1-2 strips
  - $p_1 > 0.2$
  - p_1 or $p_2 > p_{min}$

For a strip i, p_i is fractional increase:

$$p_i = \frac{\Delta E_1 - \Delta E_2}{\Delta E_2}$$

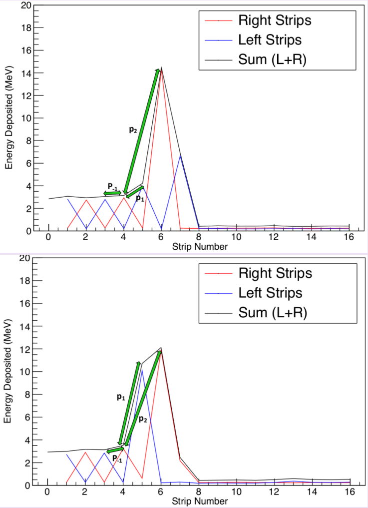


Figure 7: *A. Hood PhD Thesis 2019*

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- A sharp peak within 1-2 strips
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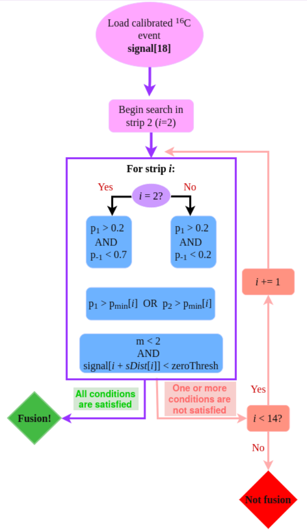
  - p_1 or $p_2 > p_{min}$
- Multiplicity, $m < 2$
- Particle stops quickly after, within *sDist*



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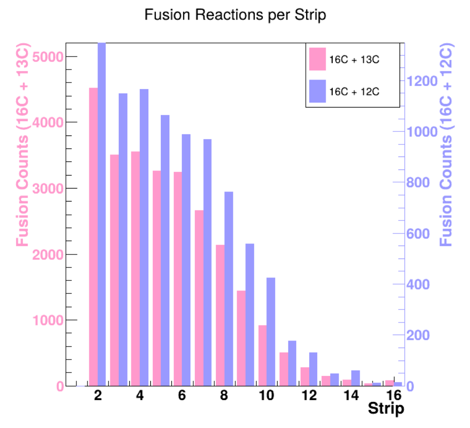


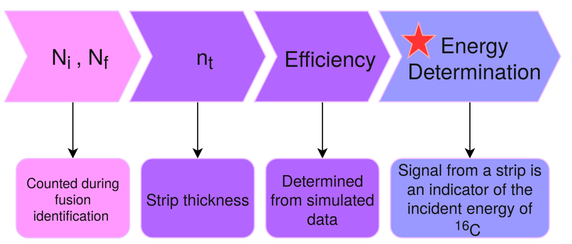
Figure 8: Number of fusion events identified in each strip for ^{16}C+^{13}C (pink, left axis) and ^{16}C+^{12}C (blue, right axis).

- Earlier strips correspond to higher energies
- higher energies $\rightarrow$ larger cross section
- higher energies $\rightarrow$ better identification efficiency

Goal:

Determine a ^{16}C + ^{12,13}C fusion cross section, $\sigma(E)$.

$$\sigma(E) = \frac{N_f(E)}{N_i(E) \times n_t} \times \frac{1}{\epsilon} \qquad (1)$$



Preliminary Results

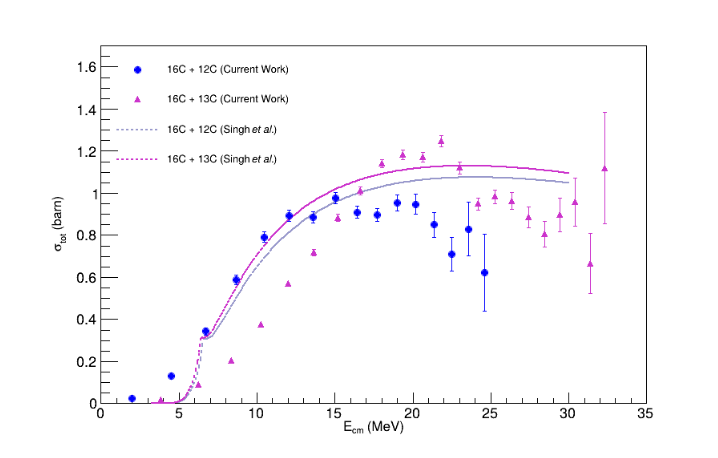


Figure 9: Total fusion cross sections for $^{16}C+^{12}C$ (blue) and $^{16}C+^{13}C$ (magenta) versus center-of-mass energy. The error bars are the statistical errors. The dashed lines show theoretical calculations from Singh *et al.* 2019 [1].

Conclusion

- Understanding neutron-rich carbon fusion helps to constrain models for X-ray superbursts
- ^{16}C + ^{12,13}C fusion cross section was measured at ANL with the MUSIC detector
- The most neutron-rich carbon fusion measurement to date!

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Next Steps:

- Quantify systematic uncertainty
- Determine impact on reaction rate

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Note:

- Development of an ML classifier tool for MUSIC data is an ongoing project

Acknowledgements

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- ANL collaborators: Dr. Daniel Santiago-Gonzalez, Dr. Melina Avila, Dr. Eilens Lopez-Saavedra, Ethan Todd
- LSU Nuclear Experiment Group!

Questions?

Extra Slides

Analysis: Energy Determination

- Significant spread in the beam energy
- Average beam energy 59.1 MeV, FWHM 12.8 MeV
- Energy loss in strip 1 is an indicator of the incident energy

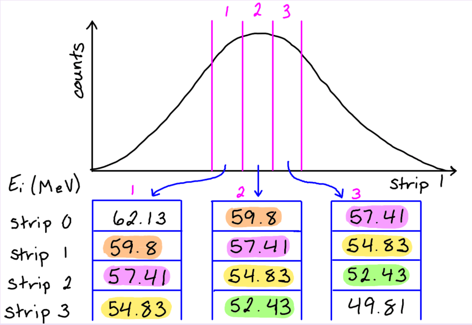


Figure 10: Sketch of the incident energy determination. Events are binned by the energy deposited in strip 1, and the incident energy for each subsequent strip is calculated for each bin (tables shown for three example bins).

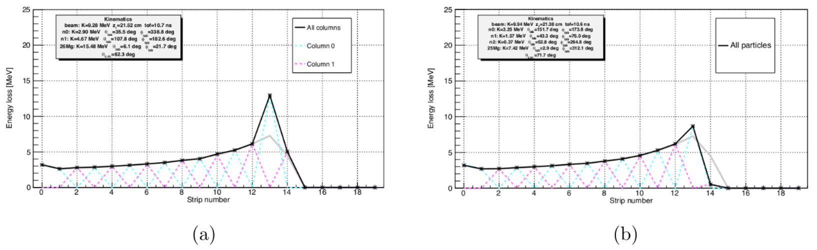


Figure 11: Simulated fusion events in MUSIC. (a) A fusion event producing a ^{26}Mg residue and (b) a fusion event producing a ^{25}Mg residue. The grey line is the expected energy loss for an unreacted particle. Simulated with [2].

- (a) is a fusion that results in a ^{26}Mg residue
- (b) is a fusion that results in a ^{25}Mg residue
- grey line is the expected Bragg curve for stopping without reacting

Strip 3 vs Strip 12 Fusion (Simulated)

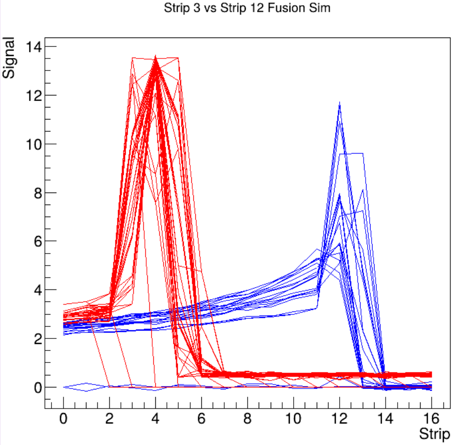


Figure 12: Simulated traces of fusion events occurring in strip 3 (red) and strip 12 (blue) in MUSIC. Simulated with [2].

Stp0 vs Stp1 Predictions

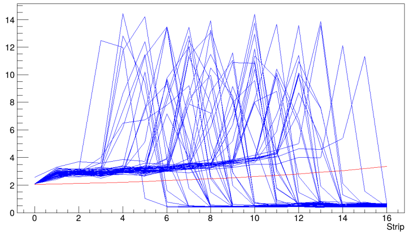


Figure 13: Event traces from a single strip 0 energy bin (blue) and the LISE++ predicted signal for an unreacted event in that energy bin (red). The prediction is not in good agreement with the traces, and the strip 0 signal is not aligned with the rest of the trace.

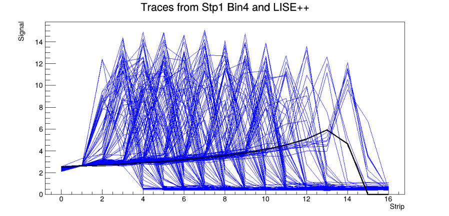


Figure 14: Event traces from a single strip 1 energy bin (blue) and the LISE++ predicted signal for an unreacted event in that energy bin (black).

- Using LISE++ to calculate the predicted trace from the strip 0 or strip 1 values
- Strip 0 is not a good predictor, strip 1 is better

Analysis: Selecting the ^{16}C Beam

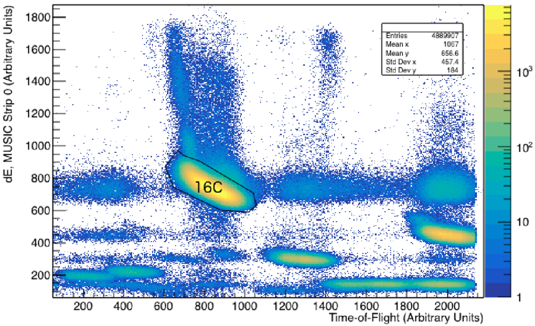
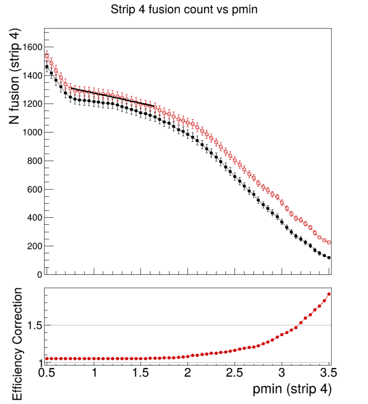
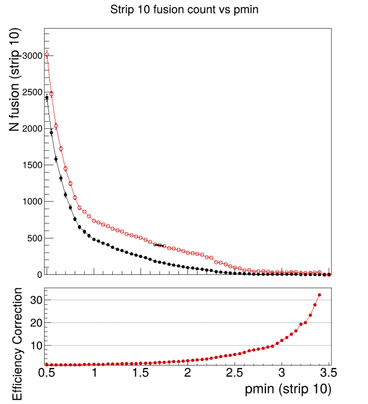


Figure 15: Particle identification plot of the energy deposited in strip 0 versus the time-of-flight as measured by the PPAC. The graphical cut selecting the incoming ^{16}C particles is shown in black. Reproduced from Ref. [3].

- Use the ΔE vs time-of-flight used for particle identification
- ^{16}C is the most intense species selected with a graphical cut (black)

Determining p_{min} values for fusion identification





Mixture of Experts Approach