Does the & Cluster Structure in Light Nuclei Persist Through the Fusion Process? Sylvie Hudan Indiana University





Does the α Cluster Structure in Light Nuclei Persist Through the Fusion Process? Sylvie Hudan Indiana University

> Physics Case Fusion Cross-section Alpha Clusters





Neutron Stars

- Accreting neutron stars provide a unique environment for nuclear reactions
 - Identified as the origin of energetic X-ray superbursts
 - As much energy in ~ 10 hours as our sun in \sim a decade
- X-ray superbursts are thought to be fueled by ¹²C + ¹²C fusion in the outer crust.
- However, the temperature of the outer crust is too low (~3x10⁶ K) for ¹²C fusion.





Neutron-Rich Light Nuclei Fusion

- Fusion of neutron-rich light nuclei (ex. ²⁴O) has been proposed to heat the crust of the neutron star and allow these superbursts
- If valence neutrons are loosely coupled to the core, then polarization can result and fusion enhancement will occur



Horowitz et al., PRC**77**, 045807 (2008) Umar et al., PRC**85**, 055801 (2012)

Neutron-Rich Light Nuclei Fusion

- Fusion of neutron-rich light nuclei (ex. ²⁴O) has been proposed to heat the crust of the neutron star and allow these superbursts
- If valence neutrons are loosely coupled to the core, then polarization can result and fusion enhancement will occur





- State of the art DC-TDHF calculations, which follow the collision dynamics, predict a fusion enhancement for neutron-rich systems
- Experimental measurements of the fusion crosssection provide a test of fusion models
- ²⁴O is currently inaccessible for reaction studies – instead study ^{18,19,20,21}O + 12C

Horowitz et al., PRC**77**, 045807 (2008) Umar et al., PRC**85**, 055801 (2012)

Sylvie Hudan, FUSTIPEN WS @ GANIL, May 2016

Fusion

- Fusion involves the amalgamation of two nuclei into a compound nucleus which no longer retains the memory of the identity or structure of the colliding nuclei (Bohr independence hypothesis)
- At low excitation, the compound nucleus de-excites by statistical emission of light particles (n,p, α)
- Limited information exists on the de-excitation of light compound nuclei formed at low excitation
- Measurement of the energy spectra, angular distributions, and cross-sections of fusion products provide a test for statistical model calculations

Experimental Approach



- The fusion cross-section can be measured by measuring the number of evaporation residues relative to incident oxygen nuclei
- To distinguish fusion residues from beam particles, need to measure:
 - Energy of the particle ($\Delta E/E \sim 2\%$)
 - Time-of-flight of the particle ($\Delta t/t \sim 7\%$)

$^{18}O + ^{12}C \rightarrow ^{30}Si^*$



- $E_{lab} = 16.25 36 \text{ MeV}$; Intensity ~ 10^5 p/s @ FSU
- Time-of-flight of beam measured between US and TGT MCP detectors
- Elastically scattered beam particles and evaporation residues (ER):
 - Time-of-flight measured between TGT MCP and Si detectors
 - Energy measured in annular Si detector

Stienbach et al., NIM**A743**, 5 (2014) Stienbach et al., PRC**90**, 041603(R) (2014) Vadas et al., PRC**92**, 064610 (2015)

Energy vs Time-Of-Flight

- Elastically scattered beam
- Scattered beam
- Clear residue island
- Alpha particles

NDIANA UNIVERSITY

$$\sigma = \frac{\mathbf{N}_{\mathrm{\tiny ER}}}{\mathbf{N}_{\mathrm{\tiny Beam}} \cdot \mathbf{t} \cdot \boldsymbol{\epsilon}_{\mathrm{\tiny ER}}}$$

- σ = fusion cross-section
- t = target thickness
- N_{Beam} = number of incident beam particles
 - N_{ER} = number of ERs measured
 - $\epsilon_{\rm \tiny ER}$ = efficiency of measuring ERs



Stienbach et al., NIM**A743**, 5 (2014) Stienbach et al., PRC**90**, 041603(R) (2014) Vadas et al., PRC**92**, 064610 (2015)

Sylvie Hudan, FUSTIPEN WS @ GANIL, May 2016

Fusion Cross-Section

- Measured the cross-section for $E_{cm} \sim 5.25$ 14 MeV
- Measured down to the 820 µb level, well below prior direct measurement of 25 mb



Stienbach et al., PRC90, 041603(R) (2014)



Comparison to DC-TDHF calculations



- Experimental and theoretical fusion excitation functions have different shapes
- At high E_{cm} DC-TDHF over-predicts the crosssection due to breakup channels not accounted for
- Dramatic increase in experimental cross-section relative to DC-TDHF occurs at energies below 7 MeV
- Increase in the ratio around the barrier can be interpreted as a larger tunneling probability
 ^{COP} narrower barrier
- Demonstrates the importance of measuring the sub-barrier fusion cross-section

Stienbach et al., PRC90, 041603(R) (2014)

Intermediate Conclusions

- Extraction of the fusion cross-section in sub-barrier domain has been accomplished by direct measurement of evaporation residues using low intensity beams
- Measurement of the fusion cross-section for ${}^{18}O+{}^{12}C$ has been made 30 times lower than previous direct measurements (820 µb level)
- Comparison of experimental cross-section with DC-TDHF predictions reveals a difference in the shape of the fusion excitation function (ie different barrier)
- Demonstrates the importance of measuring the fusion cross-section below the barrier

Residue Angular Distribution



DIANA UNIVERSITY

- Residue angular distributions are bimodal
- Recoil considerations suggest that the residues measured at large angles are associated with α emission, and small angle residues are associated with nucleon emission
- Small angle component is reasonably well described by statistical model calculations, but the large angle component is significantly underpredicted

Vadas et al., PRC92, 064610 (2015)

Residue Energy Distribution



NDIANA UNIVERSITY

 Coincident measurement of evaporation residues and α particles demonstrates that the low energy component is associated with α channels

Vadas et al., PRC92, 064610 (2015)

Sylvie Hudan, FUSTIPEN WS @ GANIL, May 2016

Direct Measurement of α Particles



INDIANA UNIVERSITY



 Experimental α angular and energy distributions are reasonably described by EVAPOR statistical model calculations

Vadas et al., PRC92, 064610 (2015)

α Cross-Section



DIANA UNIVERSITY

- As E_{c.m.} increases:
 - α emission becomes an increasingly important channel in the deexcitation process
 - The measured σ_α increasingly deviates from statistical model predictions
- σ_{α} exhibits the same $E_{c.m.}$ dependence as σ_{fusion}
- $\sigma_{\alpha} = P_{\alpha}.\sigma_{\text{fusion}}$

Vadas et al., PRC92, 064610 (2015)

Alpha Emission Probability





- P_{α} increases with increasing $E_{c.m.}$ and is enhanced in the data relative to EVAPOR
- Same features evident in other O + C systems

INDIANA UNIVERSITY Vadas et al., PRC92, 064610 (2015) Sylvie Hudan, FUSTIPEN WS @ GANIL, May 2016

Alpha Emission Probability





- P_{α} increases with increasing $E_{c.m.}$ and is enhanced in the data relative to EVAPOR
- Same features evident in other O + C systems



- Larger enhancement of ${}^{18}O + {}^{12}C$ for higher $E_{c.m.}$ suggests neutron emission is overemphasized by the statistical model
- Enhancement could be attributed to the failure of the statistical model to correctly account for α cluster structure of the projectile/target

Conclusions

- Statistical model codes underpredict the large angle component of the residue angular distributions, suggesting α emission channels are underemphasized
- Direct measurement of σ_{α} is larger than statistical model predictions, confirming that α emission is enhanced
- This enhancement is also observed for similar systems with well known α cluster structure
- These observations suggest that α cluster structure present in the projectile and target nuclei persist through the fusion process



In the Future

- Measurement performed for $^{19}O + ^{12}C$ at FSU... Stay tuned
 - Big enhancement near the barrier (~3) for ¹⁹O as compared to ¹⁸O
- Future Measurements
 - ^{39,47}K + ²⁸Si at NSCL (ReA3, Exp. 15214, Fall 2016)
 - ^{20,21(22)}O + ¹²C at GANIL (PAC proposal submitted)
 - ^{18,19}O + ¹⁸O at FSU

In the Future

- Measurement performed for $^{19}O + ^{12}C$ at FSU... Stay tuned
 - Big enhancement near the barrier (~3) for ¹⁹O as compared to ¹⁸O
- Future Measurements
 - ^{39,47}K + ²⁸Si at NSCL (ReA3, Exp. 15214, Fall 2016)
 - ^{20,21(22)}O + ¹²C at GANIL (PAC proposal submitted)
 - ^{18,19}O + ¹⁸O at FSU

Ideas for analysis and future experiments to explore clusters welcome Theoretical calculations as well....

Acknowledgments

• Indiana University:

T. Steinbach, J. Schmidt, V. Singh, B.B. Wiggins, S. Hudan, R.T. deSouza

- Florida State University:
 S. Kuvin, L. Baby, I. Wiedenhover
- Vanderbilt University:
 - A.S. Umar, V.E. Oberacker





Work supported by the US Dept. of Energy under Grant No. DEFG02-88ER-40404

Sylvie Hudan, FUSTIPEN WS @ GANIL, May 2016