Fusion of Neutron-Rich Light Nuclei: What can we learn?

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- Astrophysical interest
- Fusion dynamics
- Alpha cluster structure

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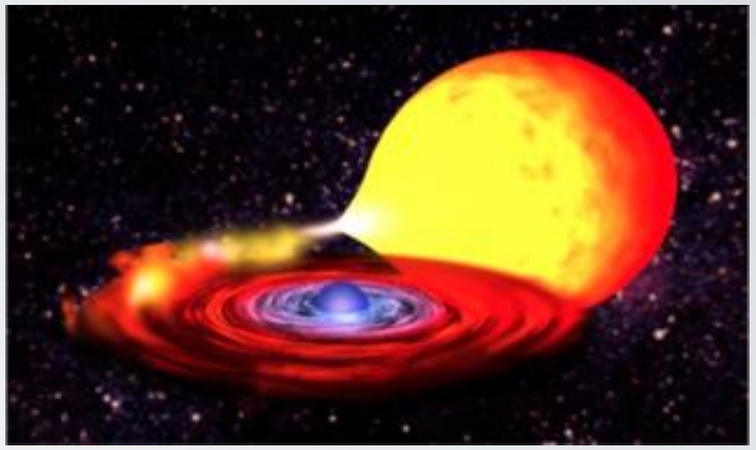
Neutron Star Crust

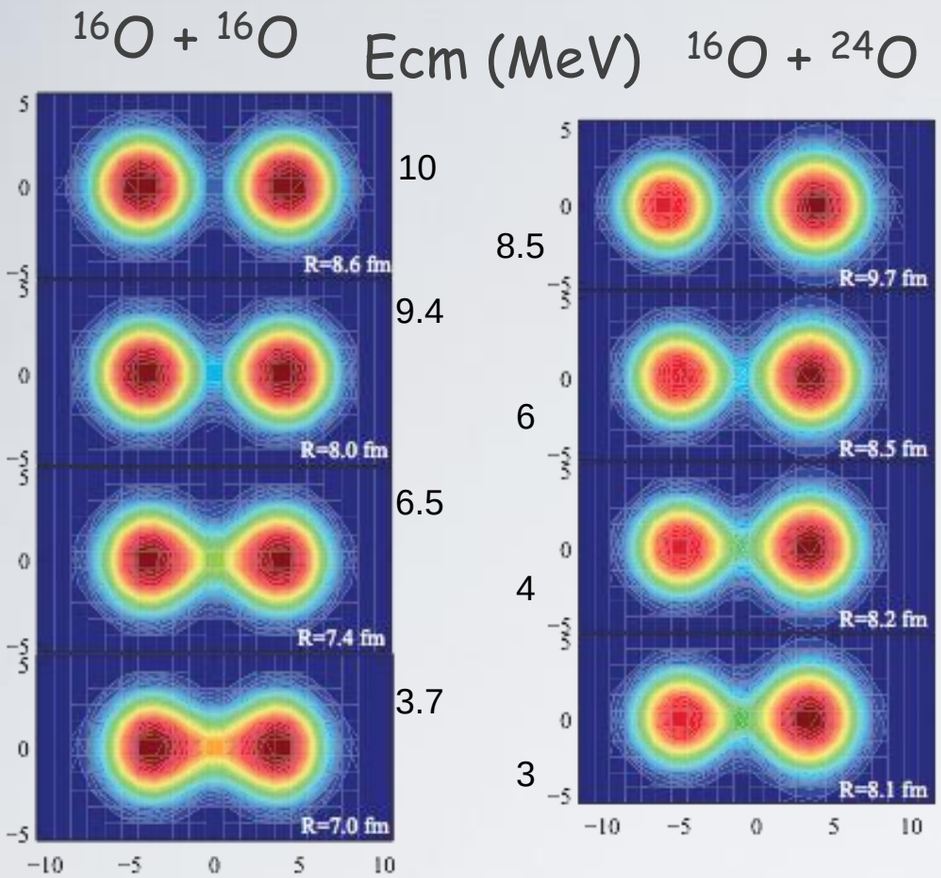
- Accreting neutron stars presents a unique environment for nuclear reactions
- Identified as the origin of energetic X-ray superbursts
  - X-ray superburst: ~10^{42} ergs
  - Annual solar output: ~10^{41} ergs



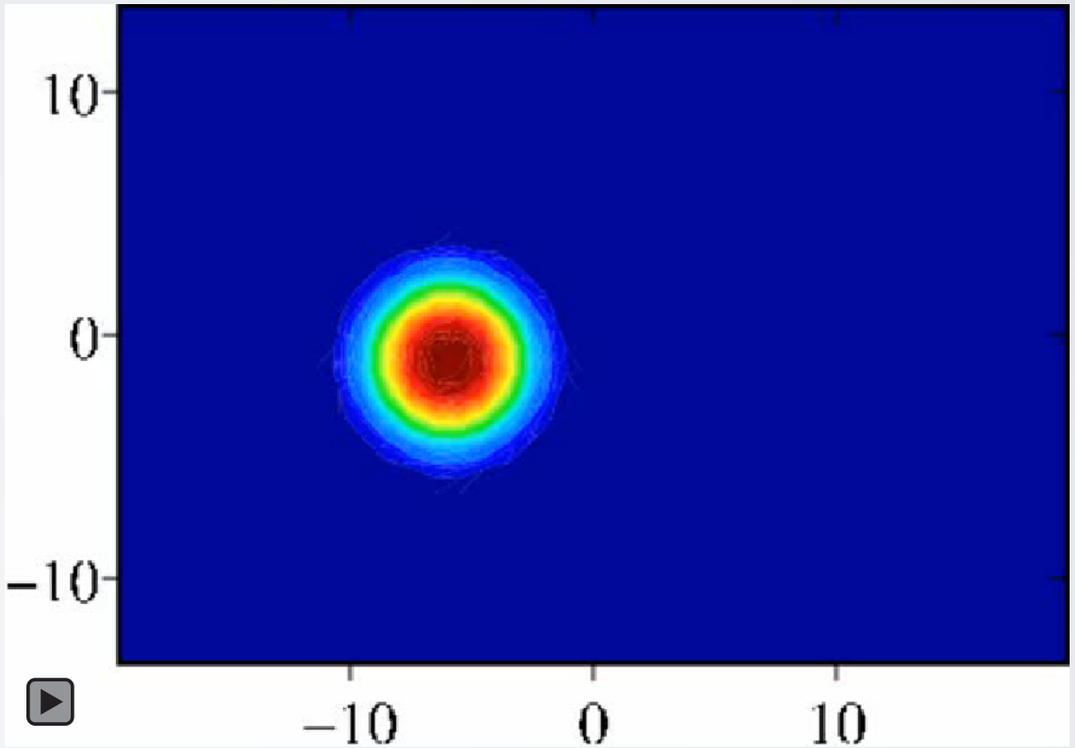
- X-ray superbursts thought to be fueled by ^{12}C + ^{12}C fusion in the outer crust
- However, the temperature of the outer crust is too low (~3×10^6 K) for ^{12}C fusion
- Neutron-rich light nuclei fusion as potential “heat source”
- If valence neutrons are loosely coupled to the core, then polarization can result and fusion enhancement will occur

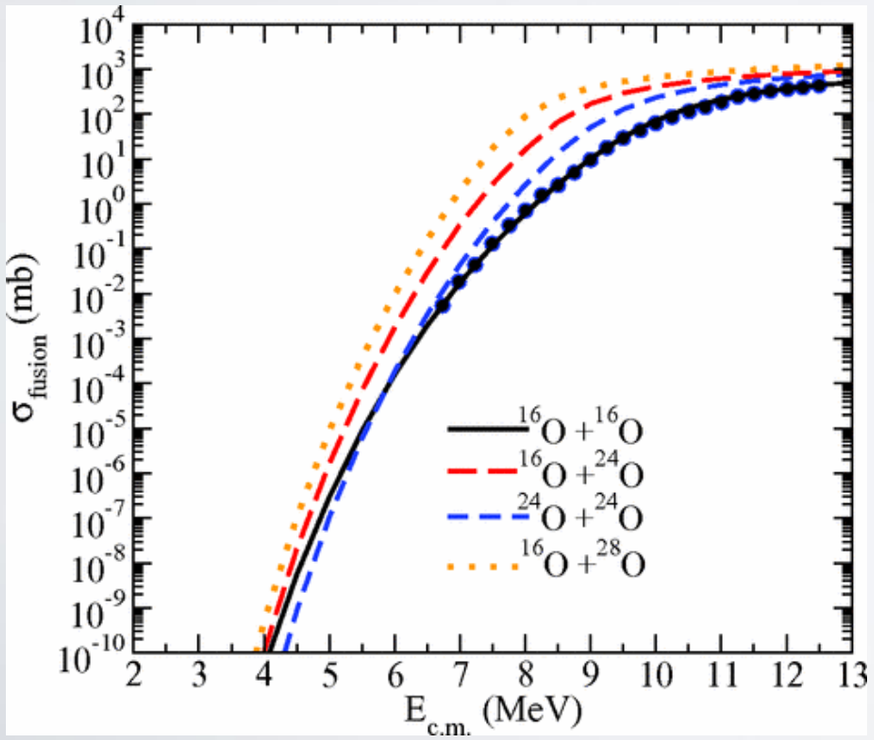
Cumming *et al.*, Astrophys. J. Lett. **559**, L127 (2001)
Strohmayer *et al.*, Astrophys. J. **566**, 1045 (2002)
Horowitz *et al.*, Phys. Rev. C **77**, 045807 (2008)
Haensel *et al.*, Neutron Stars 1, 2007

DC-TDHF and Fusion Dynamics



"For the n-rich system the barrier peak is at a larger R value since the nuclei come into contact sooner due to the extended n skin of the ^{24}O nucleus."



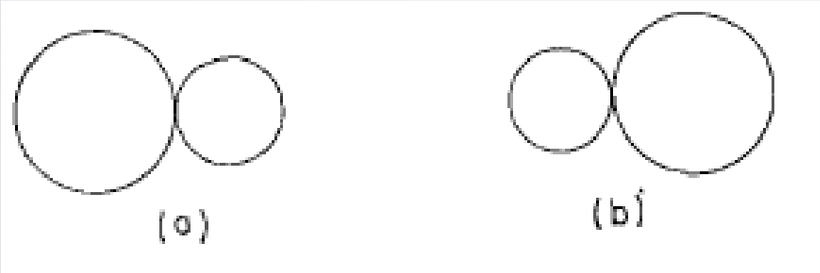


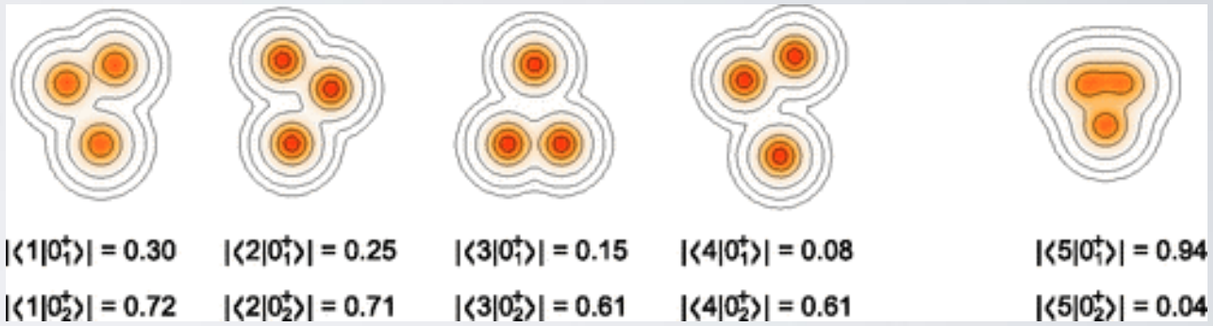
- Neck formation, surface vibrations and density fluctuations observed
- Enhancement of the fusion cross-section at and below the barrier related to neutron transfer for n-rich systems and dynamical effects

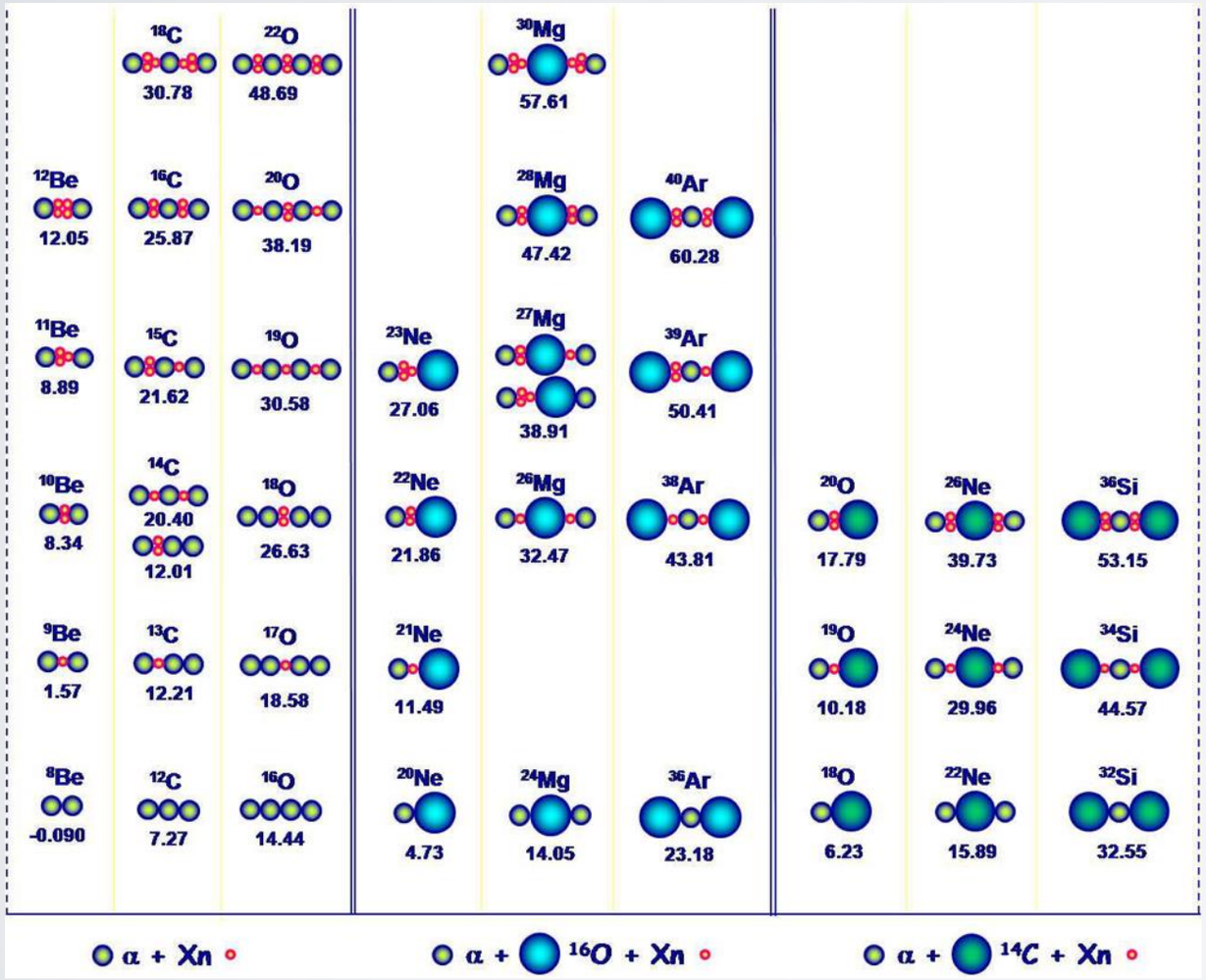
DC-TDHF calculations:
A.S Umar et al., PRC **85**, 055801 (2012)

Alpha Cluster Structure

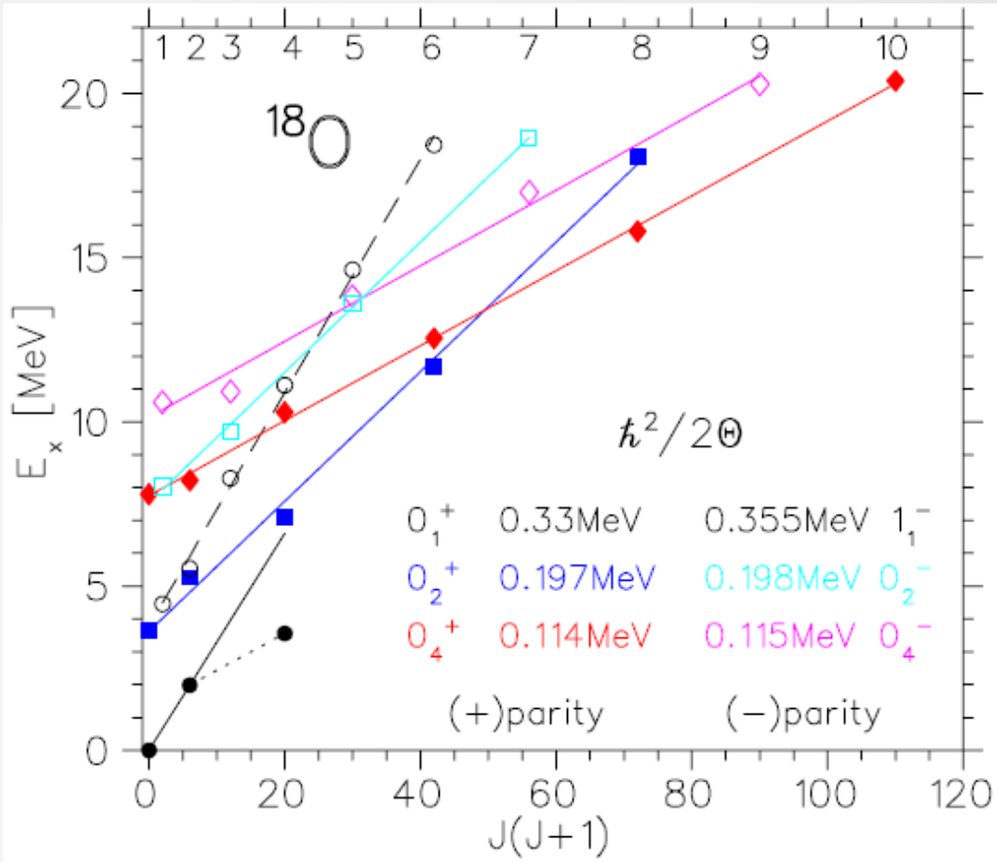
- Alpha cluster structure has been predicted and observed for light nuclei





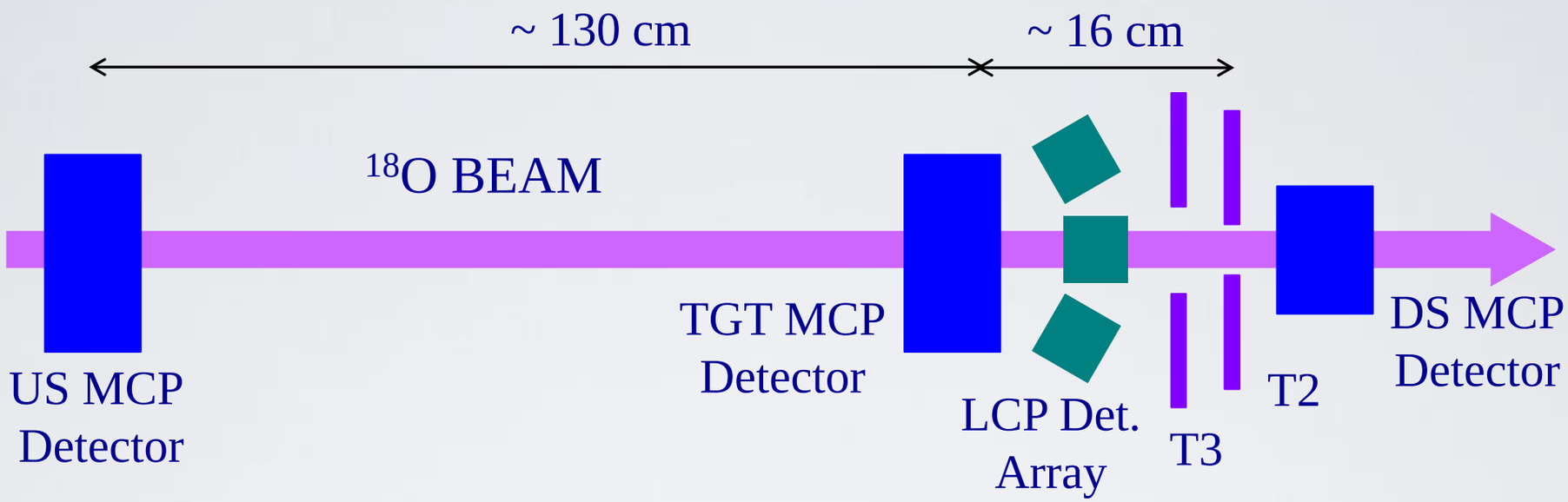


- Observation of rotational bands



Horiuchi and Ikeda, Prog. of Th. Phys. **40**, 277 (1968)
Chernykh *et al.*, PRL**98**, 032501 (2007)
von Oertzen *et al.*, EPJA**43**, 17 (2010)
von Oertzen, Int. J. of Mod. Phys. E**20**, 765 (2011)

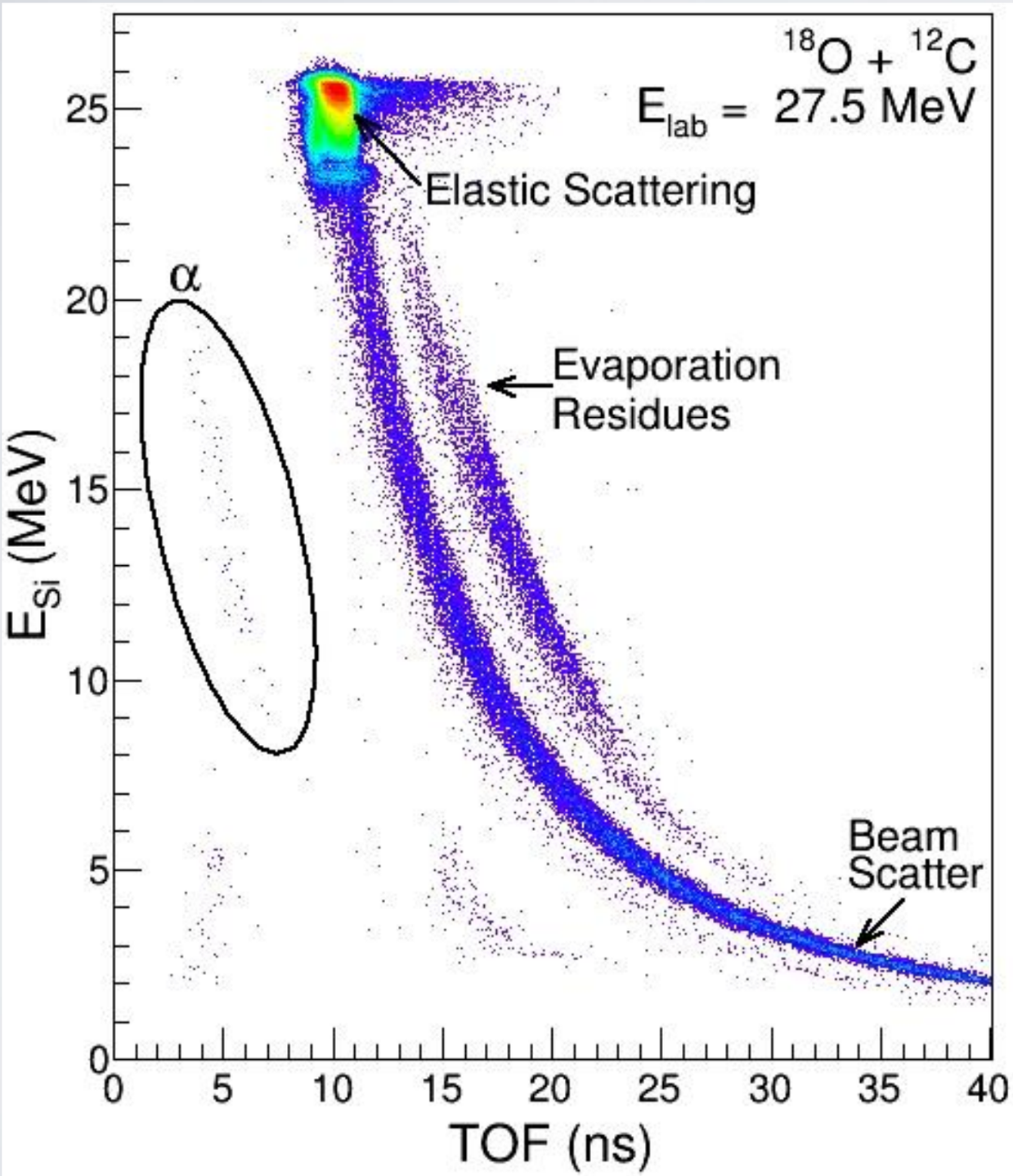
Fusion Studies with Low Intensity Beams



- MCP detectors: start for TOF, beam counting, beam cleaning
  - ExB design to minimize scattering
- Fusion residues detected in segmented Si detectors: stop for TOF, energy and angle
  - Sub-nanosecond time resolution, small dead layer, lowest segmentation as possible
- Decay products (p/alpha) detected in Si detectors and CsI(Tl) array
- Maximum beam intensity: ~5×10^5 pps

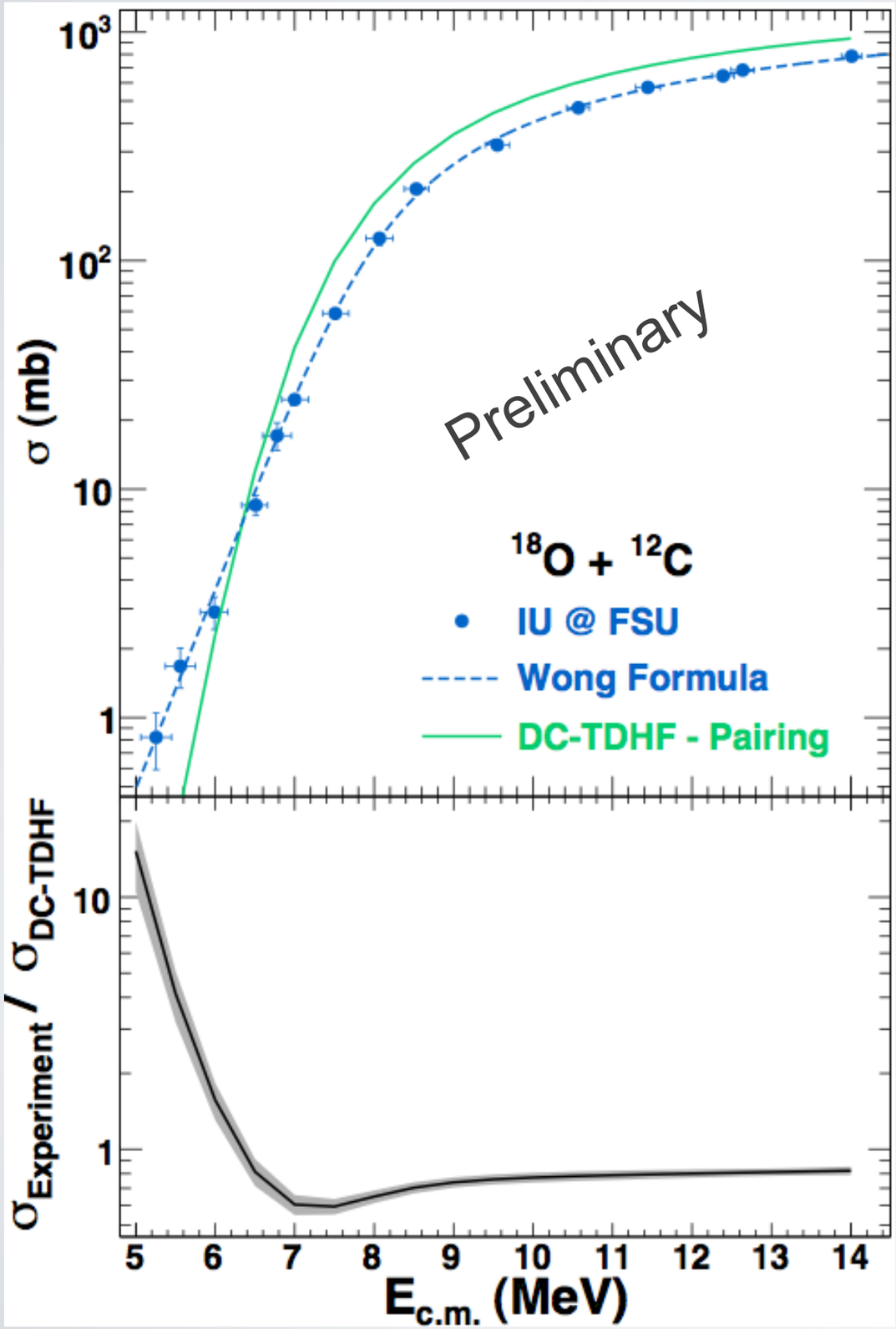
T.K. Steinbach *et al.*, NIMA**743**, 5 (2014)

Extracting Fusion Residues



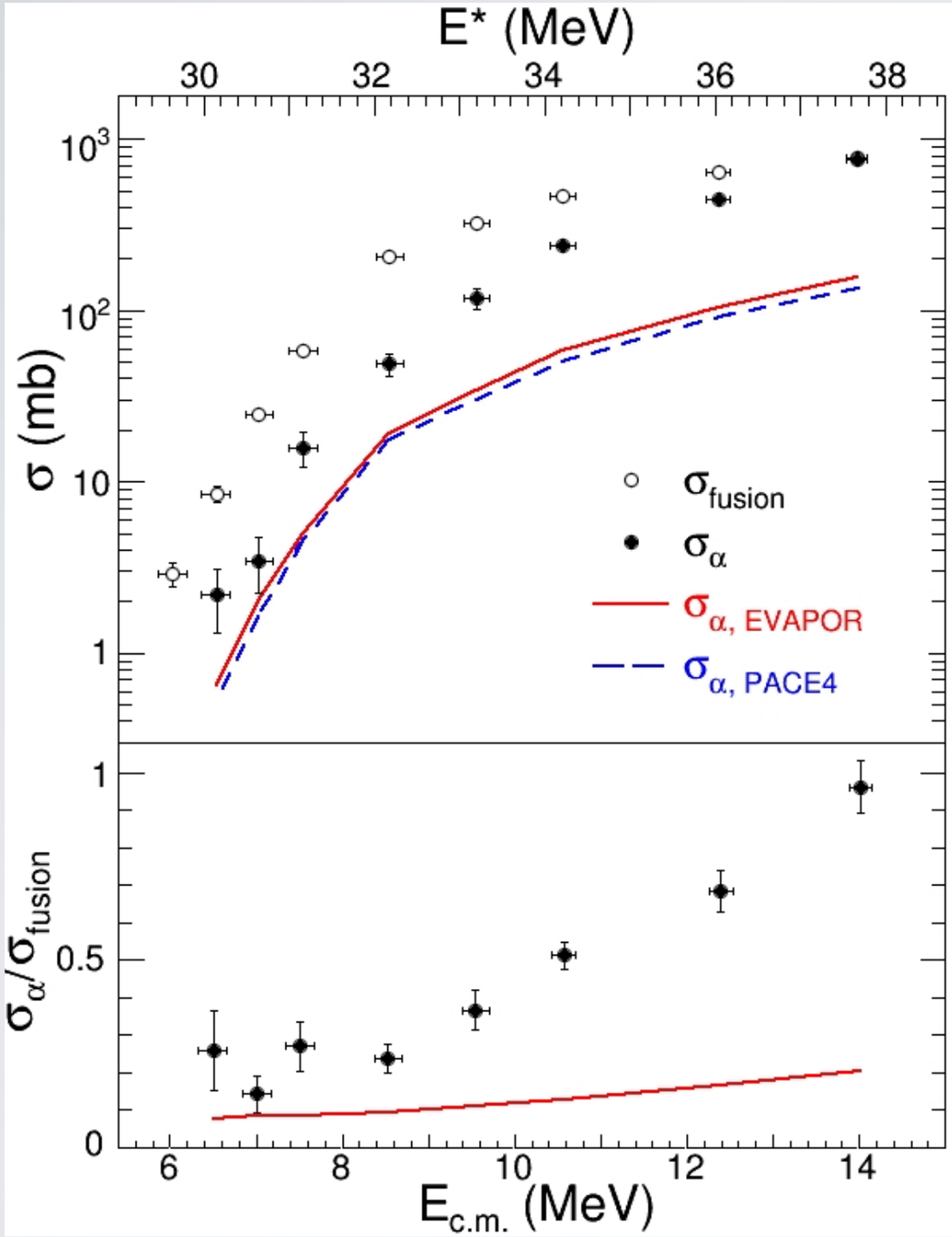
- Evaporation residues identified by energy and time-of-flight
  - Elastic scattering
  - Beam Scatter (largely reduced with ExB MCP detector)
  - Evaporation residue island
  - Emitted particles (p, α)
- Evaporation residues
  - Count: fusion cross-section
  - Energy, Angle, A (via TOF)

Fusion Cross-Section

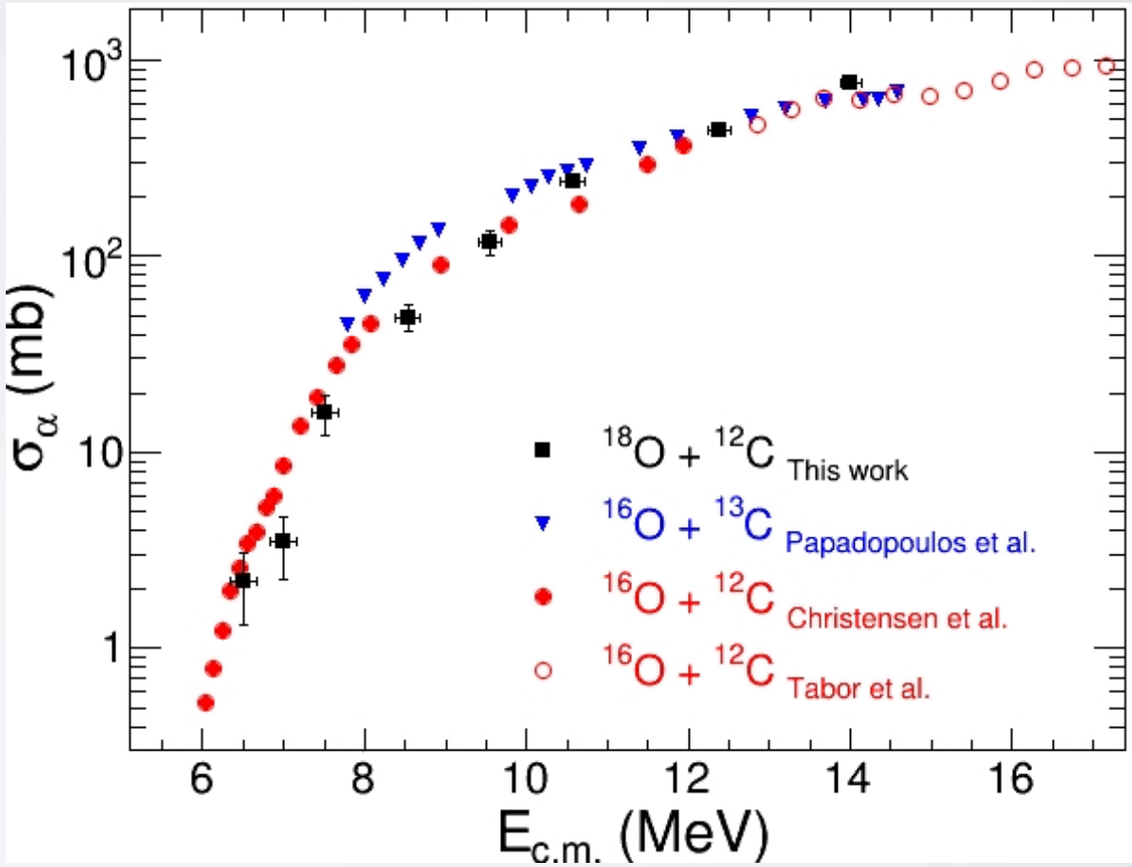


- Cross-section measured down to 820 μb
- At higher $E_{c.m.}$: $\sigma_{expt}/\sigma_{DC\text{-}TDHF} \approx 0.75$
  - Breakup reactions
- For sub-barrier energy: slower fall off of the experimental cross-section as compared to TDHF
  - Larger tunneling probability for the experiment: Narrower barrier?
  - Lack of pairing evolving in time in TDHF?

Alpha Cluster Structure



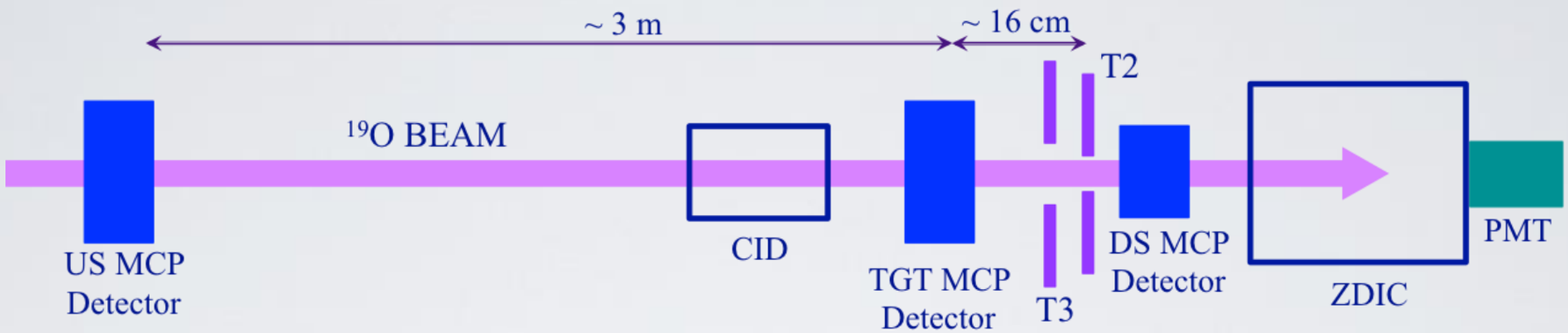
- Statistical codes under-estimate experimental α cross-section
- Relative enhancement relative is energy dependent



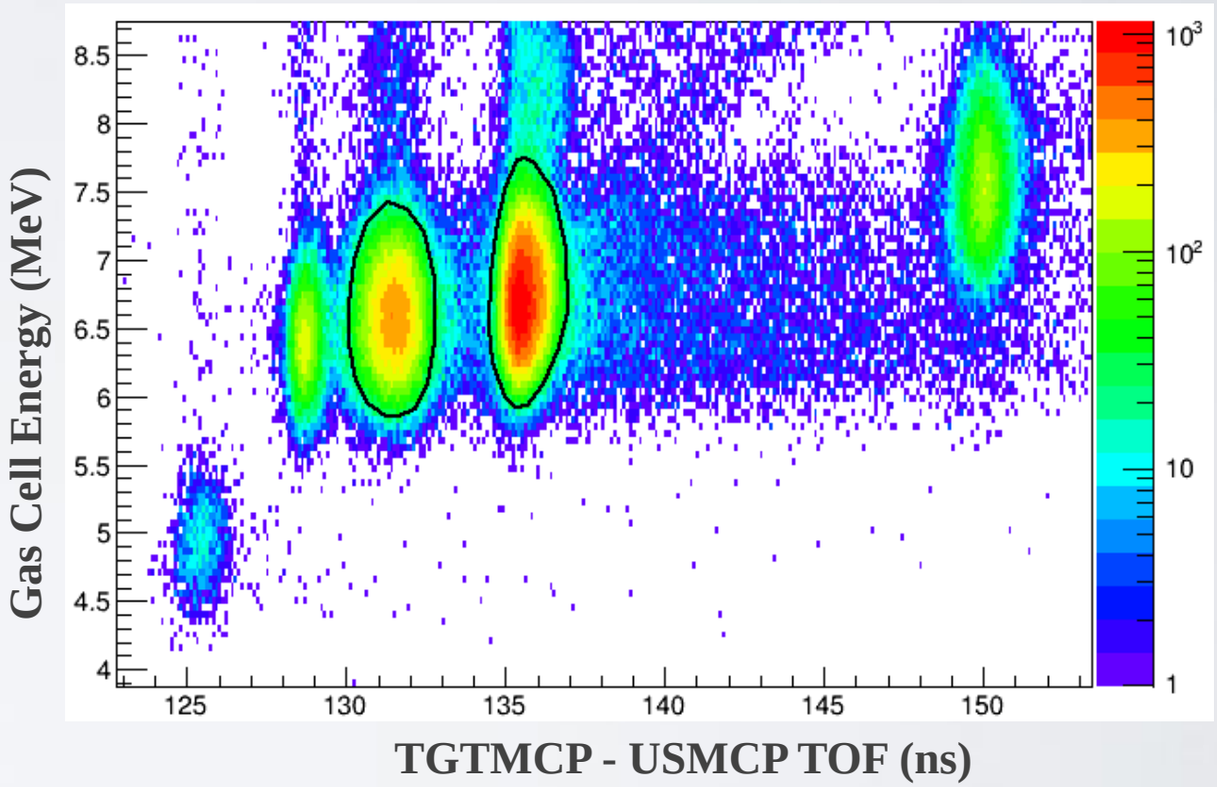
- Similarity of the α cross-section for different systems as a function of $E_{c.m.}$

- **Pre-existing α cluster structure in the entrance channel**
- **Collision dynamics**

$^{19,18}O + ^{12}C$ @ Florida State U.

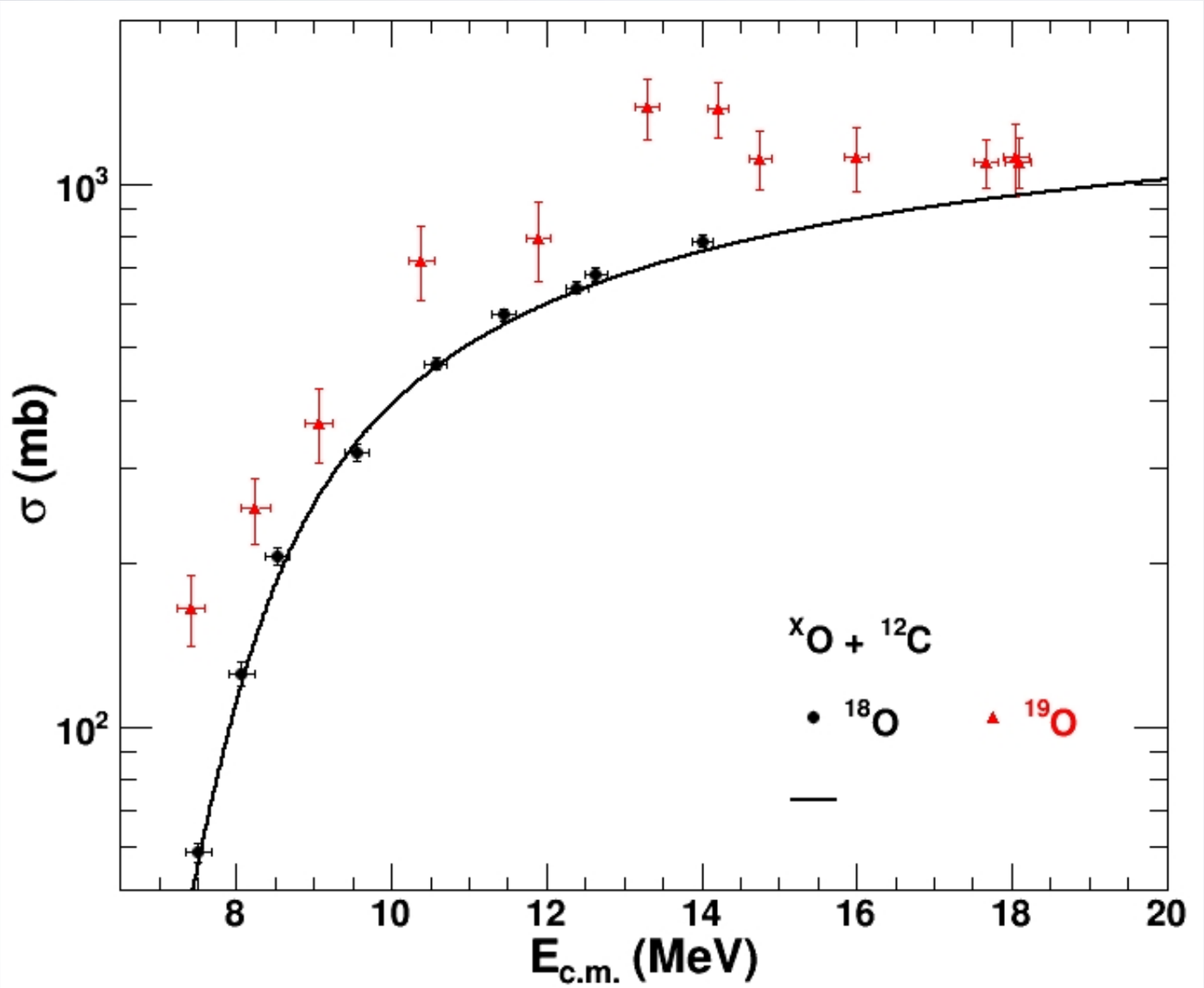


- Beam characteristics:
  - $^{18}O(d,p)^{19}O$
  - ^{18}O @ ~75 MeV
  - D_2 target: P ~ 350 Torr, T ~ 77K
  - Beam on target: ~1-2x10^4 pps
  - Beam purity: 25 - 50 % ^{19}O



- Active Degrading Ion Chamber (CF_4): energy change and **PID event by event**
- Simultaneous measurement of RIB and know reference beam

$^{19}O+^{12}C$



- Measured fusion cross-section for ^{19}O + ^{12}C from $E_{c.m.}$ ~ 7.5 to 18 MeV
- Hint of a small enhancement
- Cross-reference system for systematics errors assessment
- Data also taken for ^{17}F and ^{16}O

Conclusion and Future At ReA3

- Ability to measure fusion of with low intensity beams
  - Cross-section to the 800 μb level
  - Decay channels, in particular alpha channels
- Near term at ReA3: $^{39,47}K + ^{28}Si$ (15214)
  - Addition of a third Si detector at small angles to measure ~75% of residues
- Future needs
  - Systematic fusion measurement with neutron-rich “light” nuclei
  - At **and below the barrier** to maximize barrier change with neutron number
  - Beam intensity: 10^4 – few 10^5 pps

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