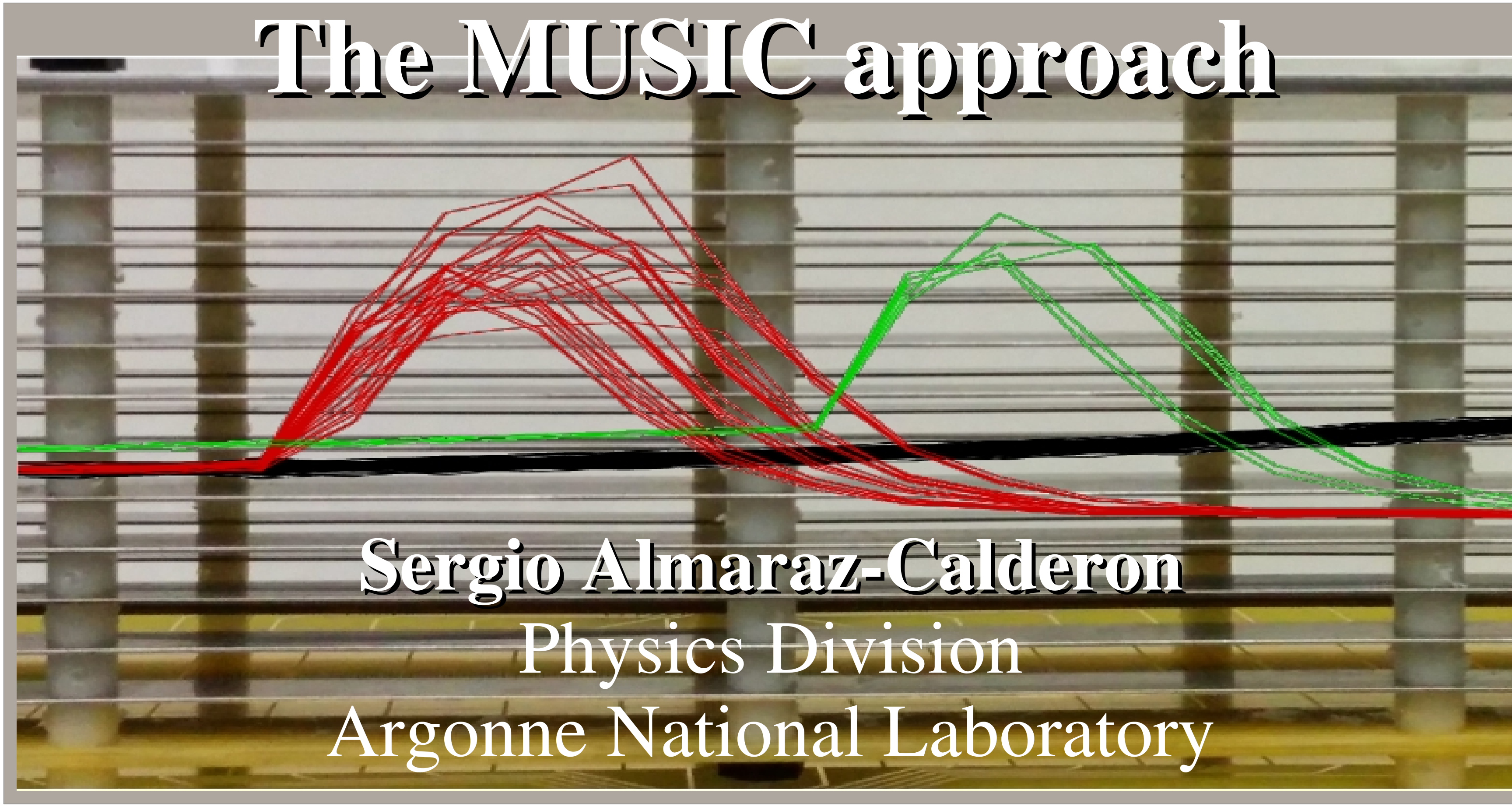
Fusion reactions in nuclear astrophysics:

The MUSIC approach



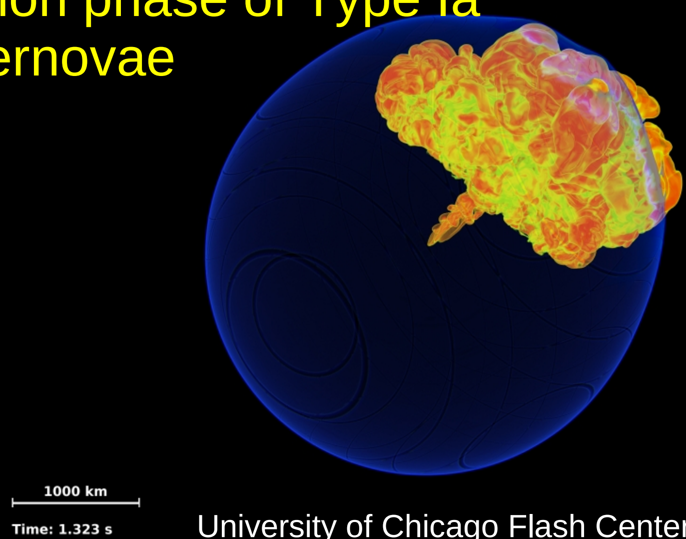
Sergio Almaraz-Calderon
Physics Division
Argonne National Laboratory

2014 ATLAS USER'S MEETING
05/15/2014

Carbon burning reactions in the stars

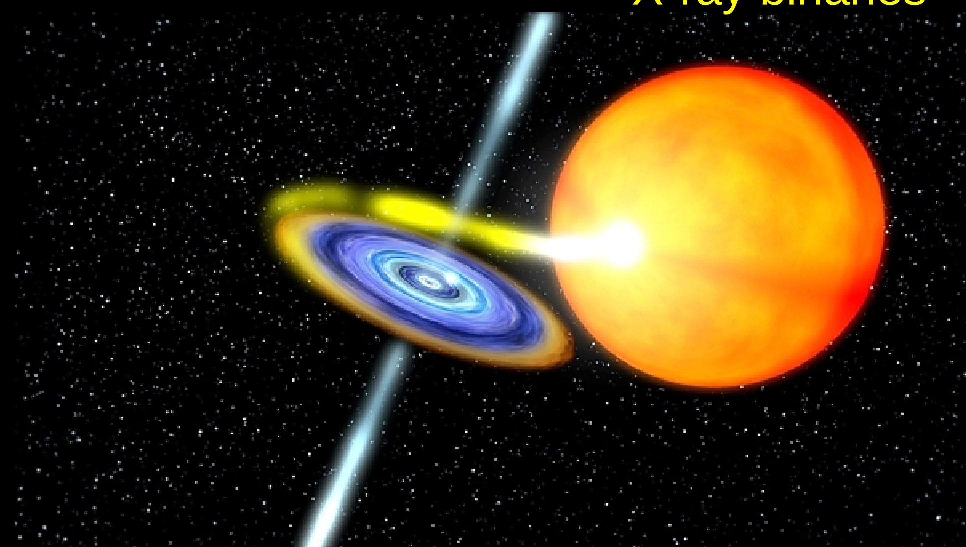
Carbon burning in massive stars

Ignition phase of Type Ia supernovae

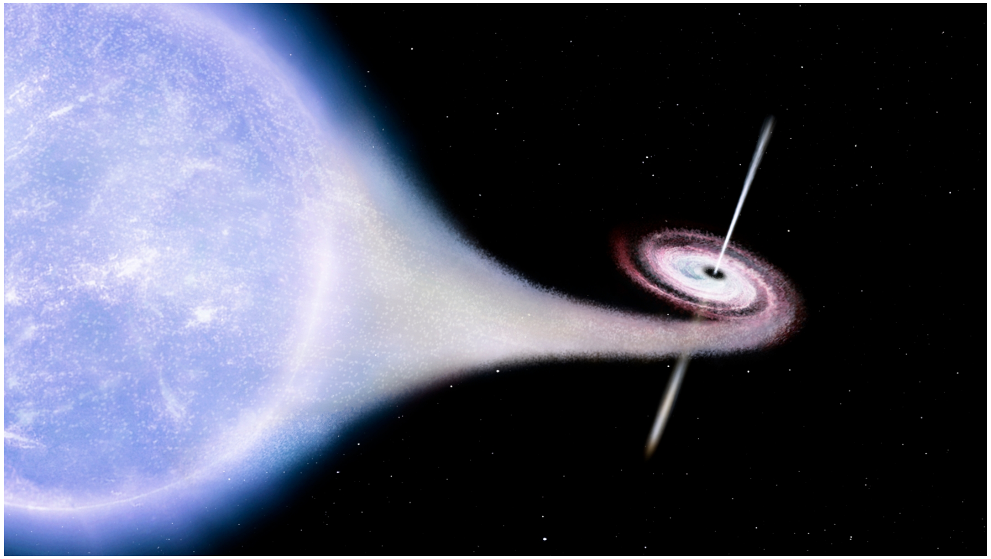


University of Chicago Flash Center

X-ray binaries



X-Ray Bursts and Superbursts

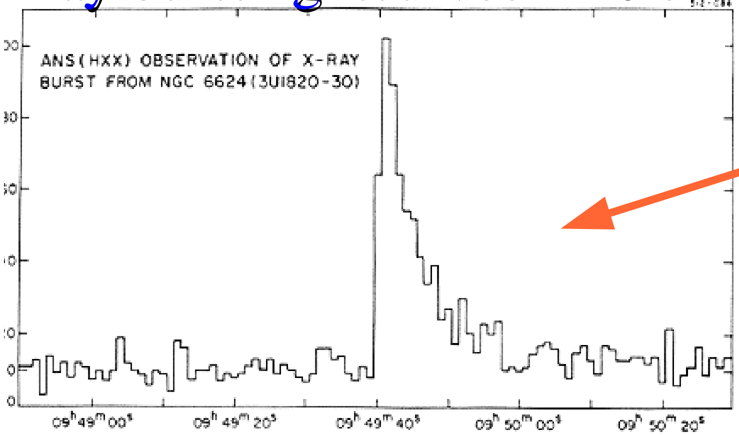


Accreting neutron star

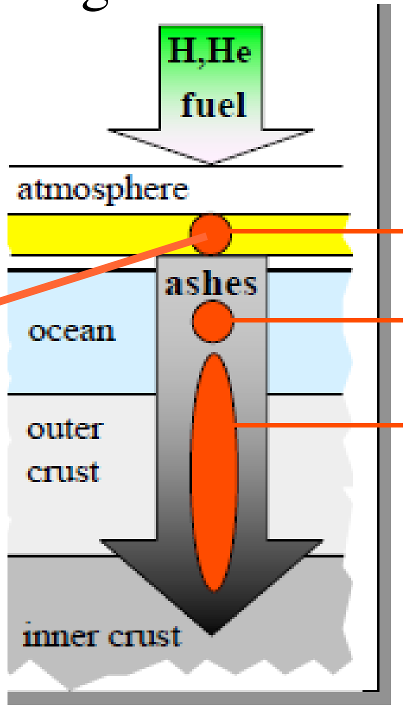
M ~ 1 – 2 M⊙
R ~ 10 km
P ~ 10^{14} g/cm^3

Accretion rate ~
0.5–50 kg/cm^2/s of H or He

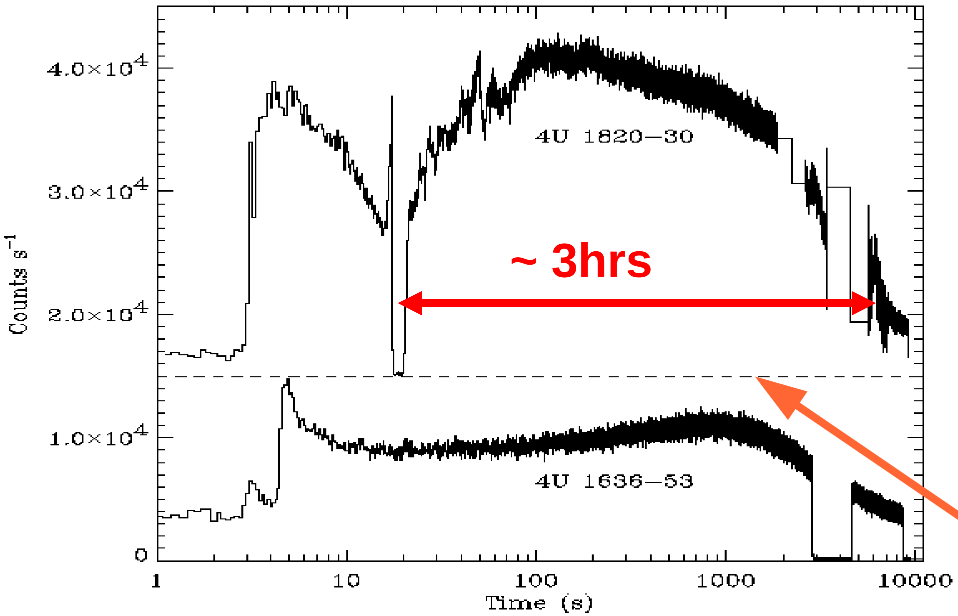
- H and He burning (rp-process)
- X-ray burst lightcurves ~ 10 sec – minutes



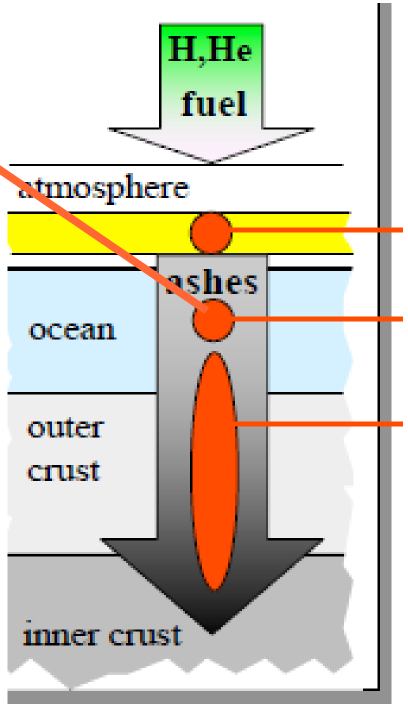
Normal burst



H. Schatz



Superbursts



H. Schatz

What powers the ‘superbursts’?

Deep burning: Carbon fusion

Fusion of neutron-rich light nuclei (C, O, Ne) $^{12}C + ^{12}C....^{24}C + ^{24}C$

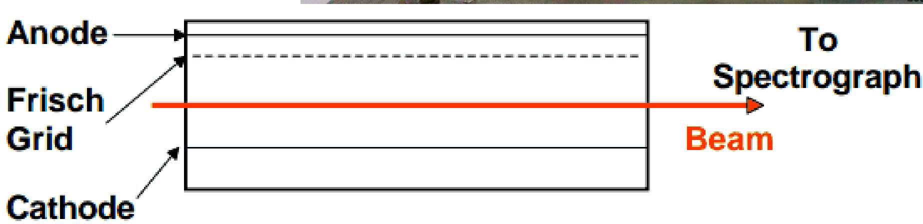
D.G. Yakovlev et al., Phys. Rev. C 82, 044609 (2010).

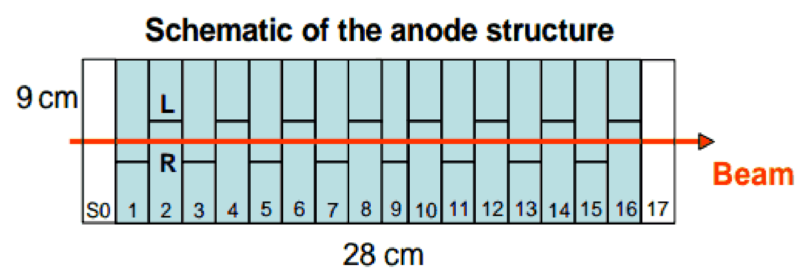
X.D. Tang et al., J. Phys.Conf. Ser. 381, 012120 (2012).

MUSIC

*MU*lti-*S*ampling *I*onization *C*hamber

- Medium size high efficiency active target / gas-filled detector
- Measurement of energy losses along a particle track
- Measurement of excitation function with a single beam energy



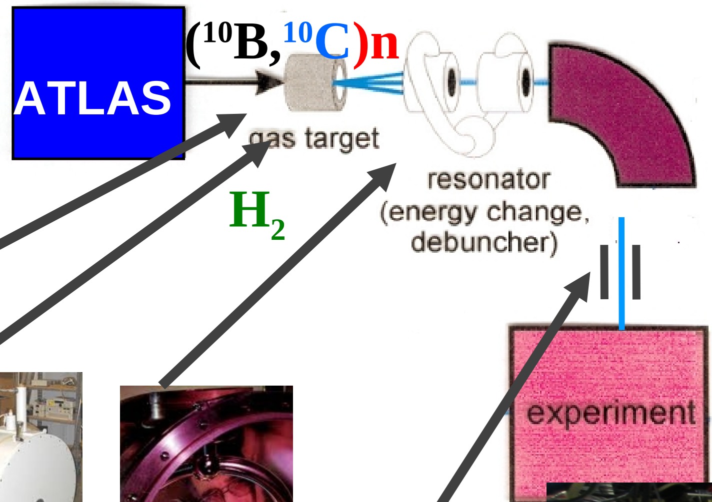


$^{10,12,13,14,15}C + {}^{12}C$ experimental campaign

Radioactive beam production at ATLAS:

In-Flight technique

^{10}B, E~ 80 MeV
~ 100 pnA



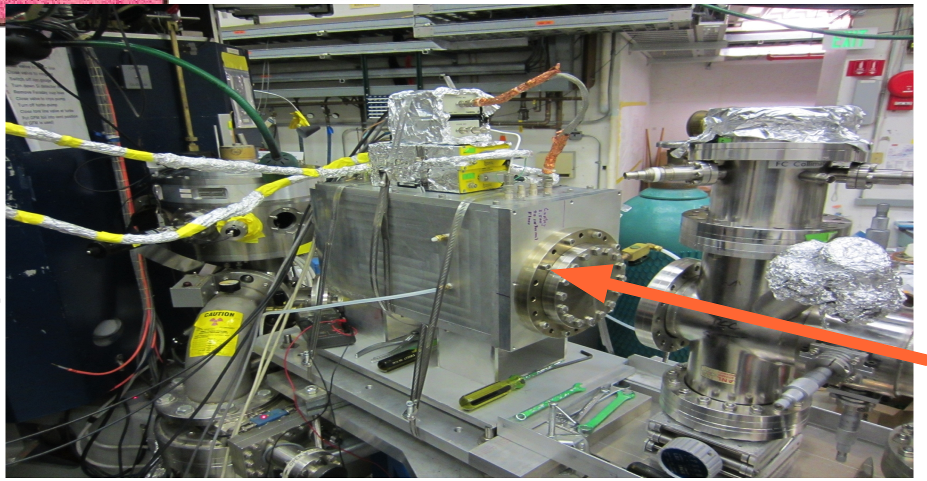
- ^{10}C: $^{1}H(^{10}B,^{10}C)n$: 500/s
- [^{11}C: $^{2}H(^{10}B,^{11}C)n$]: 2000/s
- ^{12}C
- ^{13}C
- ^{14}C
- ^{15}C: $^{2}H(^{14}C,^{15}C)p$: 2000/s

Multiple gas cells

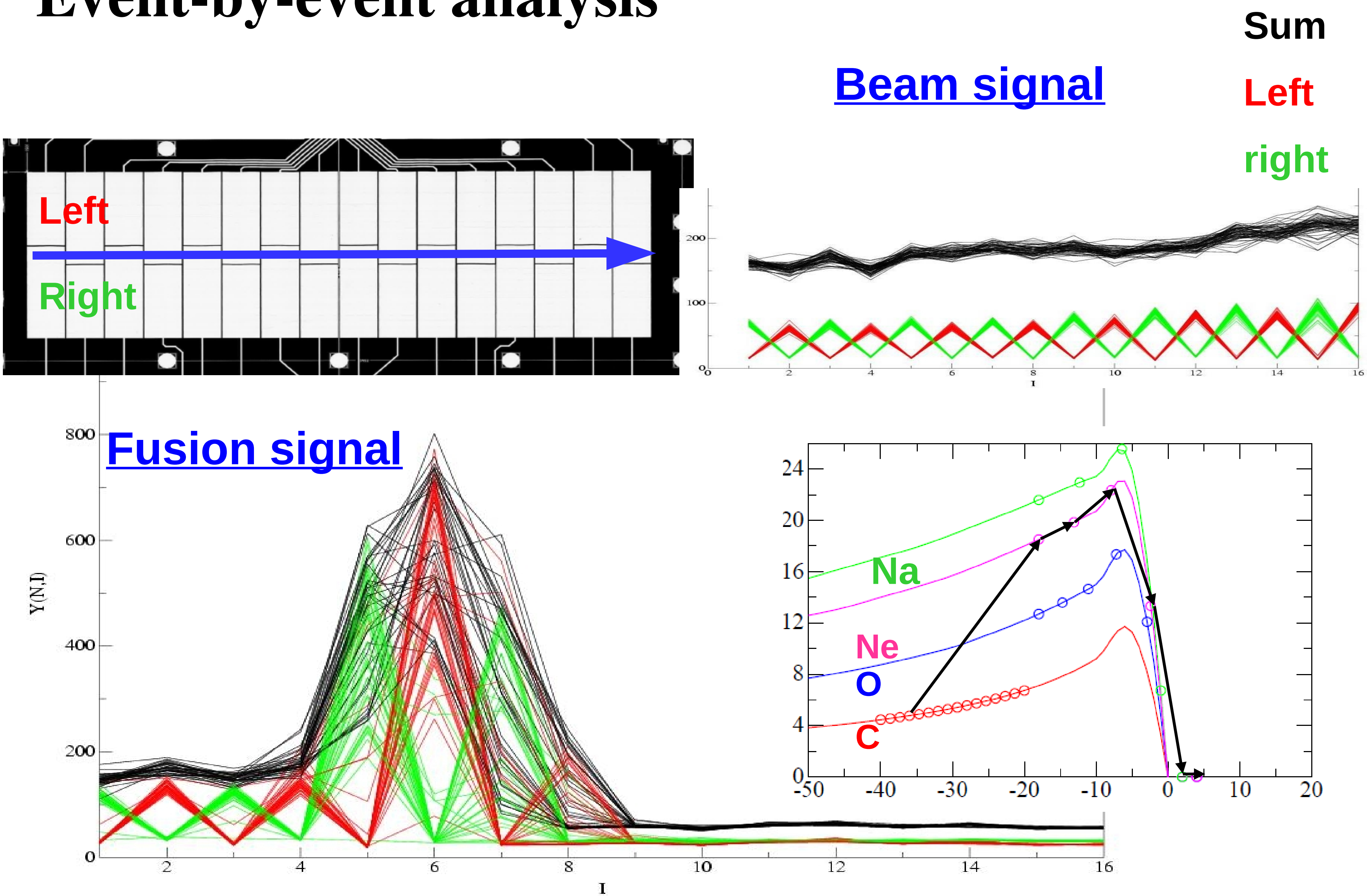
Superconducting solenoid

Debunching resonator

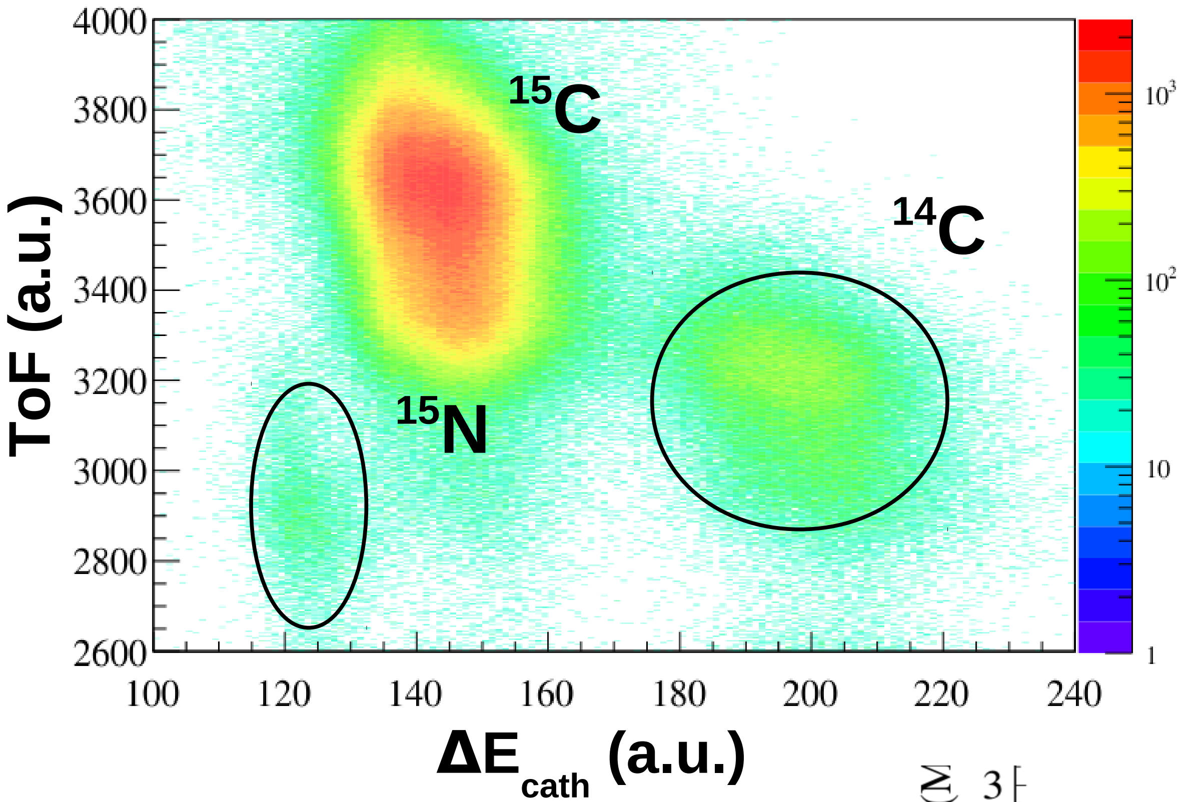
rf sweeper

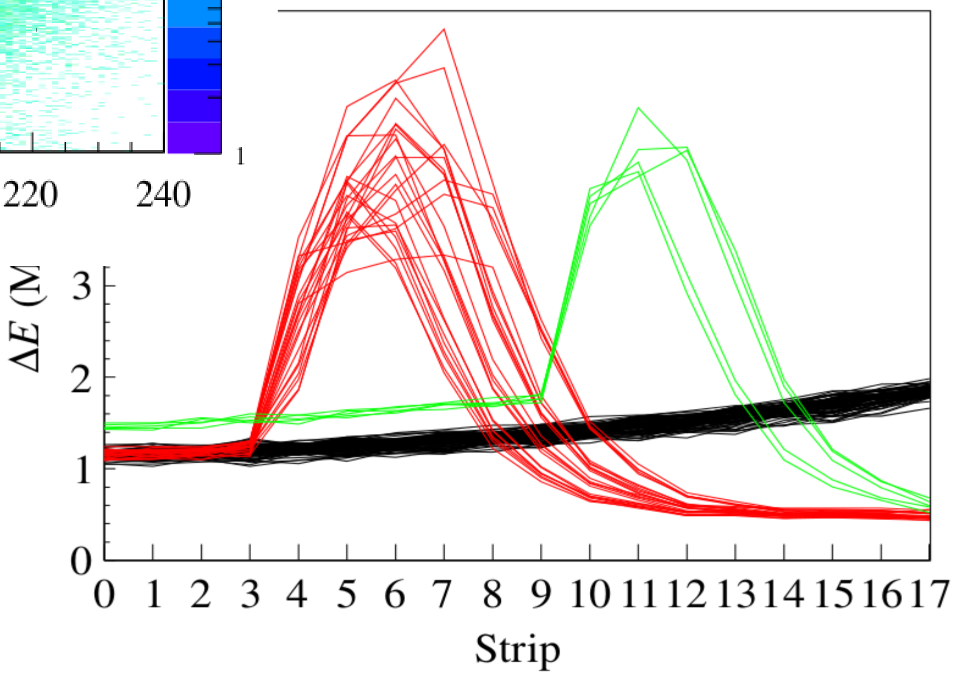


Event-by-event analysis

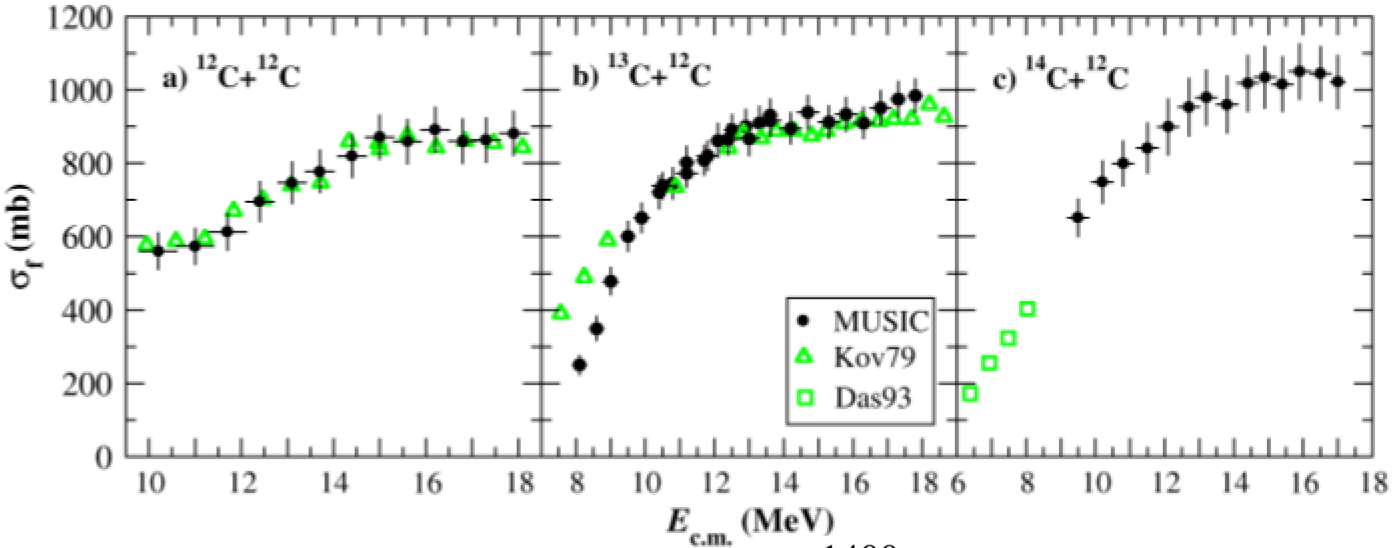


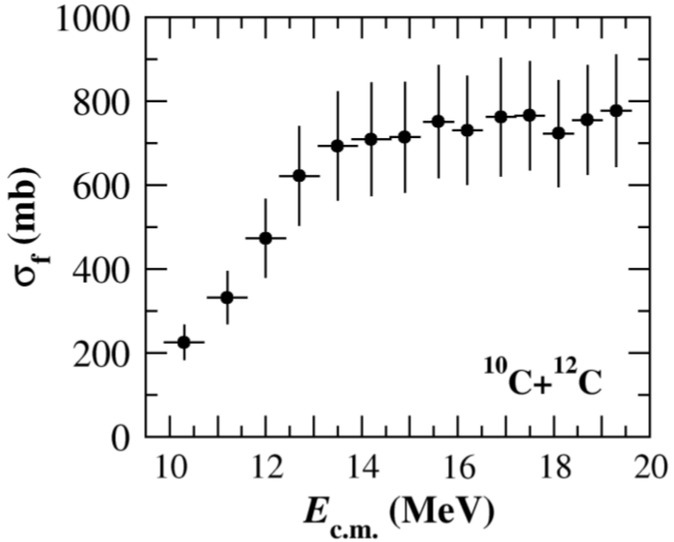
MUSIC performance with Radioactive ion beams

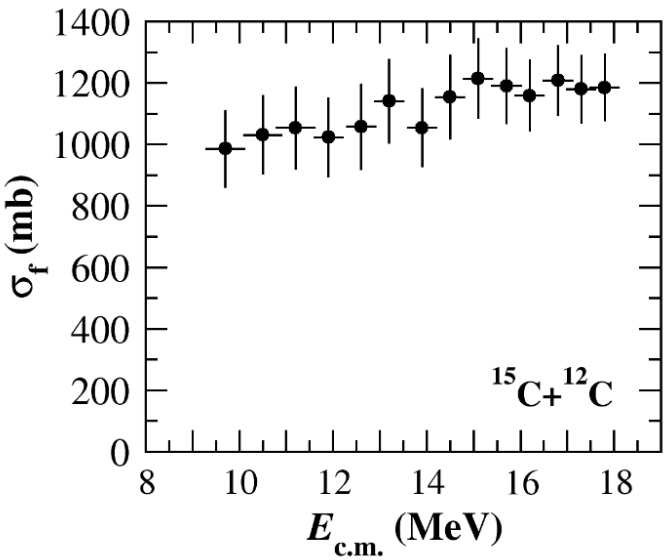




Results


a) $^{12}C+^{12}C$
b) $^{13}C+^{12}C$
c) $^{14}C+^{12}C$
MUSIC
Kov79
Das93
σ_f (mb)
$E_{c.m.}$ (MeV)


$^{10}C+^{12}C$
σ_f (mb)
$E_{c.m.}$ (MeV)

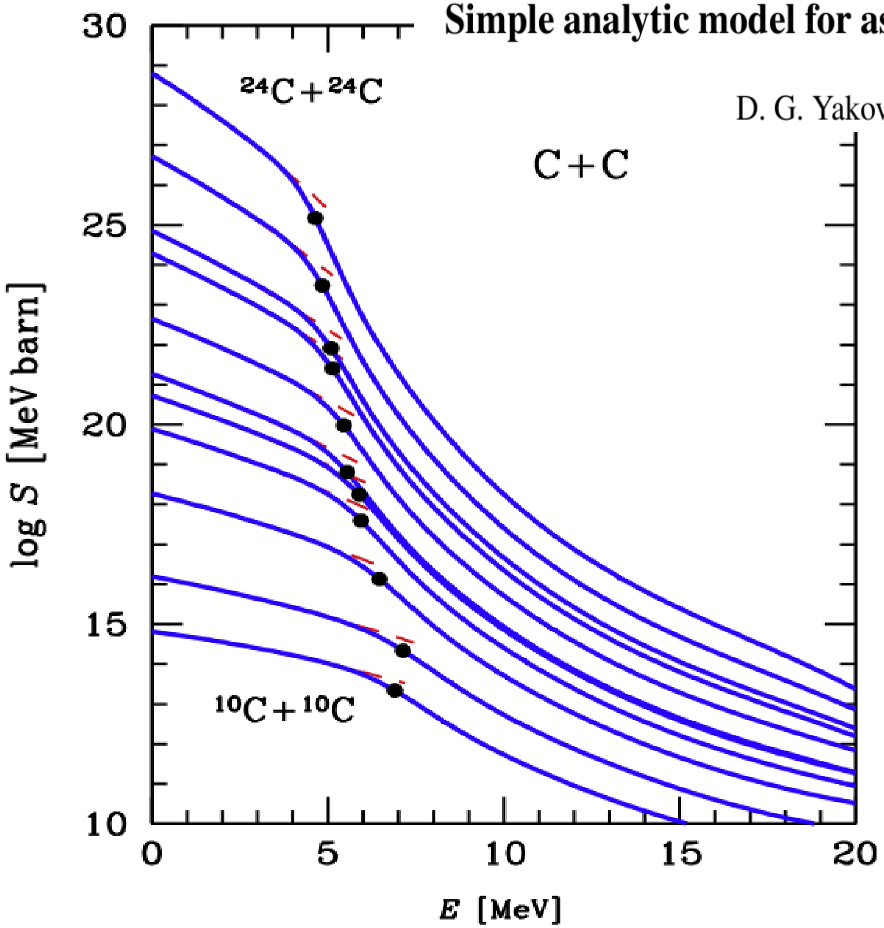

$^{15}C+^{12}C$
σ_f (mb)
$E_{c.m.}$ (MeV)

What powers the ***'superbursts'***?

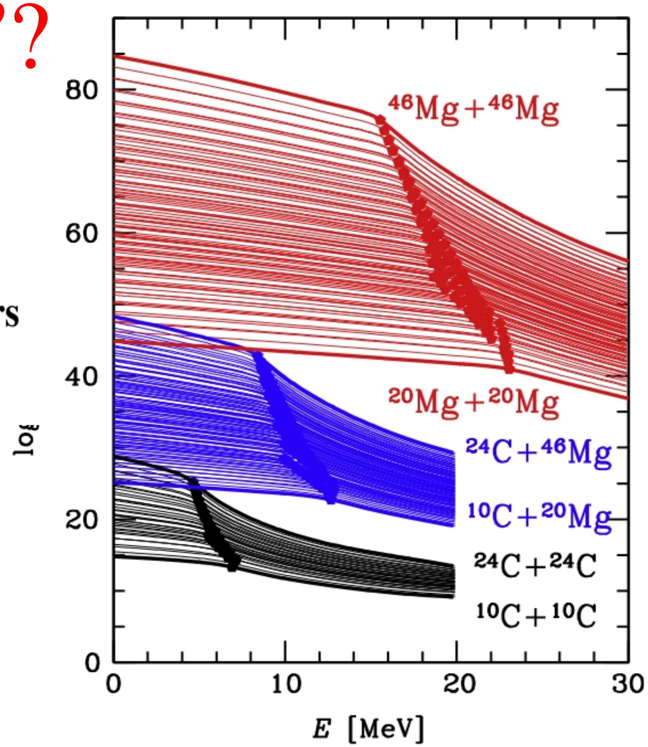
PHYSICAL REVIEW C **82**, 044609 (2010)

Simple analytic model for astrophysical *S* factors

D. G. Yakovlev



M. Beard et al. / Atomic Data and Nuclear Data Tables 96 (2010) 541–566

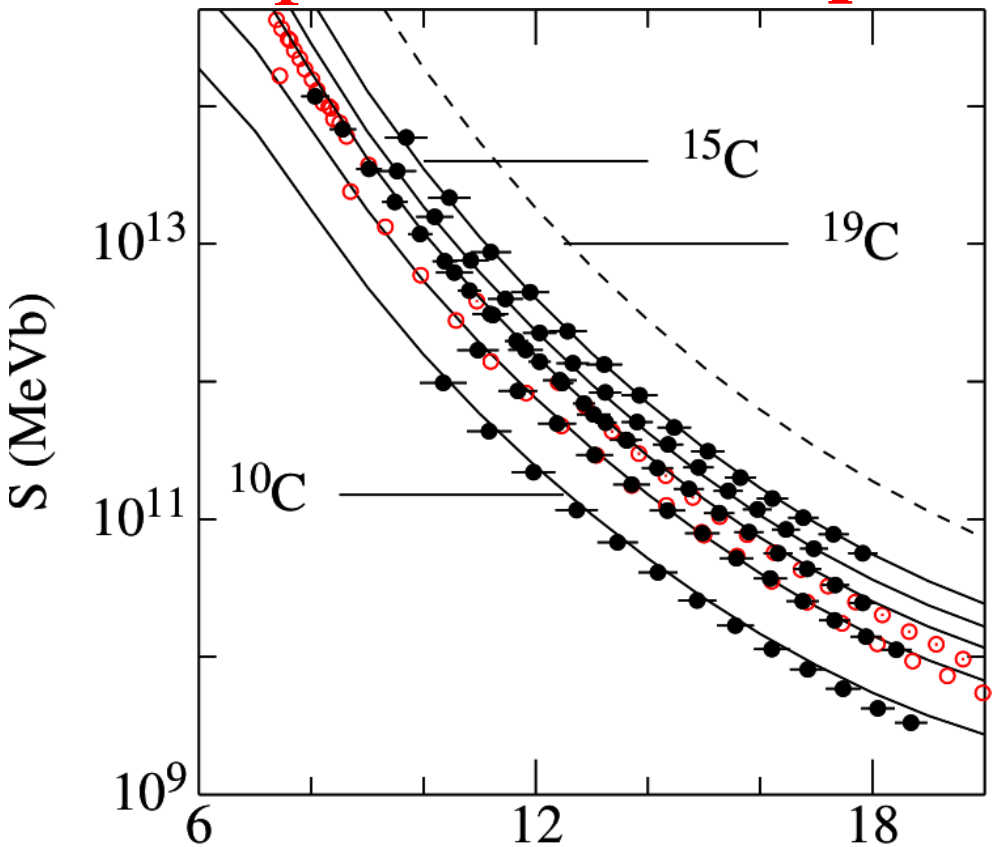


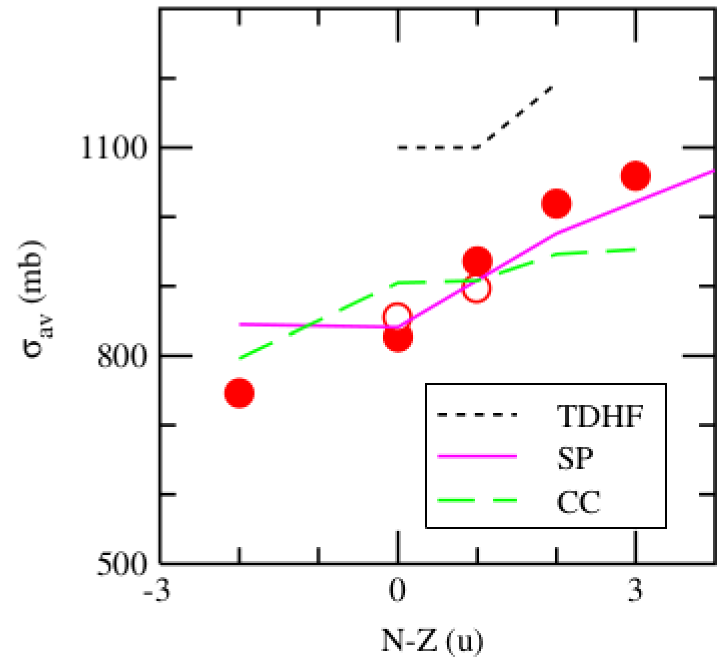
$$S(E) = \exp\left\{B_1 + B_2 E + B_3 E^2 + \frac{C_1 + C_2 E + C_3 E^2 + C_4 E^3}{1 + \exp\left[(E_C - E)/D\right]}\right\}.$$

$$\sigma(E) = E^{-1}\exp(-2\pi\eta)S(E).$$

$$\eta = \frac{Z_a Z_A e^2}{\hbar}\sqrt{\frac{\mu}{2E}},$$

What powers the *'superbursts'*?





PRL **112,** 192701 (2014) PHYSICAL REVIEW LETTERS week ending 16 MAY 2014

Measurements of Fusion Reactions of Low-Intensity Radioactive Carbon Beams on ^{12}C and their Implications for the Understanding of X-Ray Bursts

P. F. F. Carnelli,[1,2,3] S. Almaraz-Calderon,[1] K. E. Rehm,[1] M. Albers,[1] M. Alcorta,[1,*] P. F. Bertone,[1,†] B. Digiovine,[1] H. Esbensen,[1] J. O. Fernández Niello,[2,4] D. Henderson,[1] C. L. Jiang,[1] J. Lai,[5] S. T. Marley,[1,‡] O. Nusair,[1] T. Palchan-Hazan,[1] R. C. Pardo,[1] M. Paul,[6] and C. Ugalde[1]

Summary

We have performed the first measurements of the total fusion cross sections in the systems $^{10,14,15}C + {}^{12}C$ using a new active target-detector system.

In the energy region accessible with existing radioactive beams a good agreement between the experimental and theoretical cross sections is observed.

Future work

Digital MUSIC

Measure exit channels

$^{12}CH_4 + {}^{14,16,18,19,20}O$

$^{12}CH_4 + {}^{20,21,22,23,24}Ne$

$^{20,22}Ne + {}^{20,21,22,23,24}Ne$

$^{208}Pb + {}^{20,21,22,23,24}Ne$

…

Aknowledgements

<u>P. F. F. Carnelli, K. E. Rehm</u>, M. Albers, M. Alcorta, M. Avila, B. Digiovine, H. Esbensen, D. Henderson, C. L. Jiang,1 J. Lai, O. Nusair, R. C. Pardo, M. Paul, D. Santiago-Gonzalez, and C. Ugalde

Thank you!