Measurements related to nuclear astrophysics and clustering with Nu-ball and STELLA

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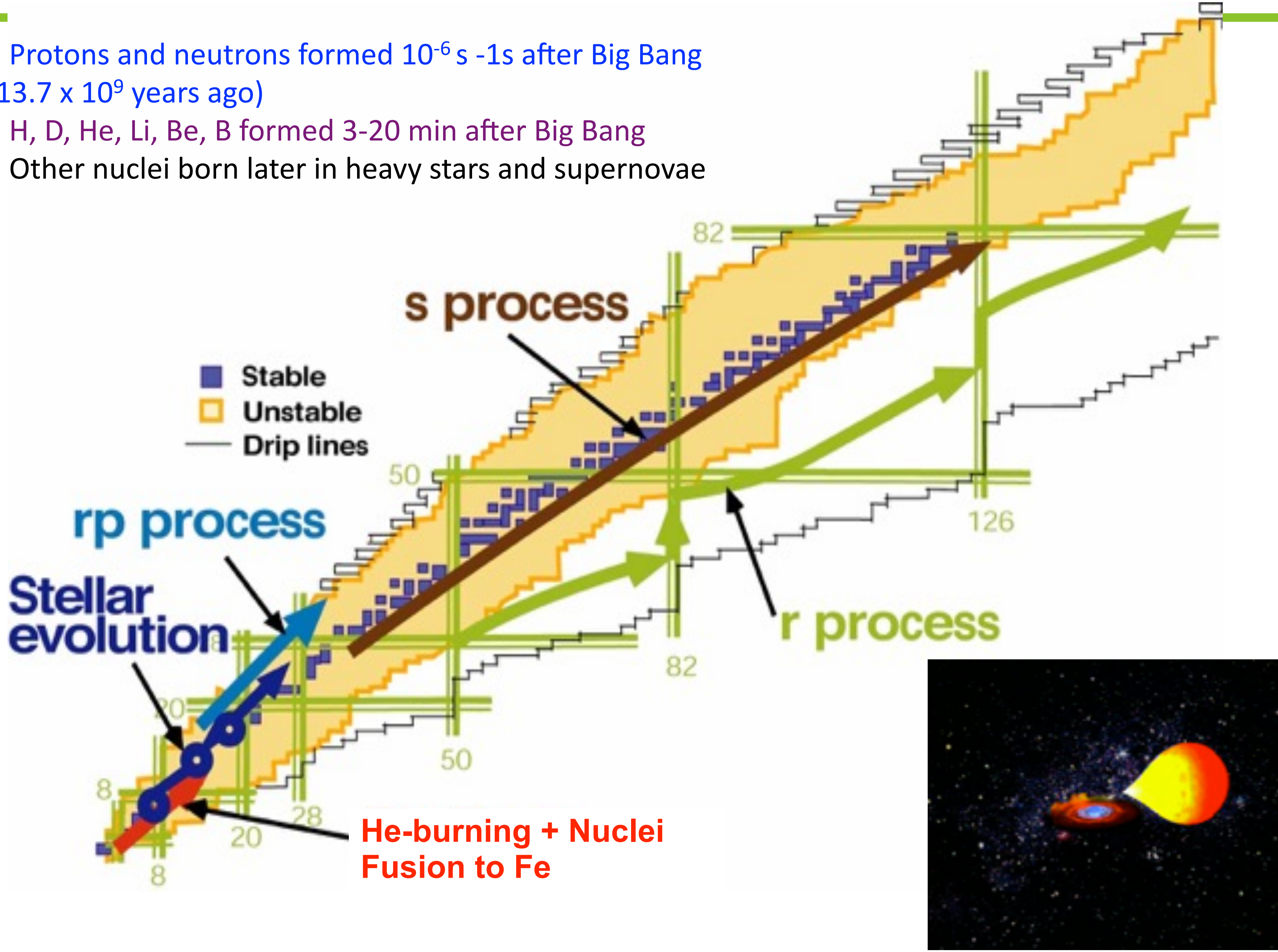
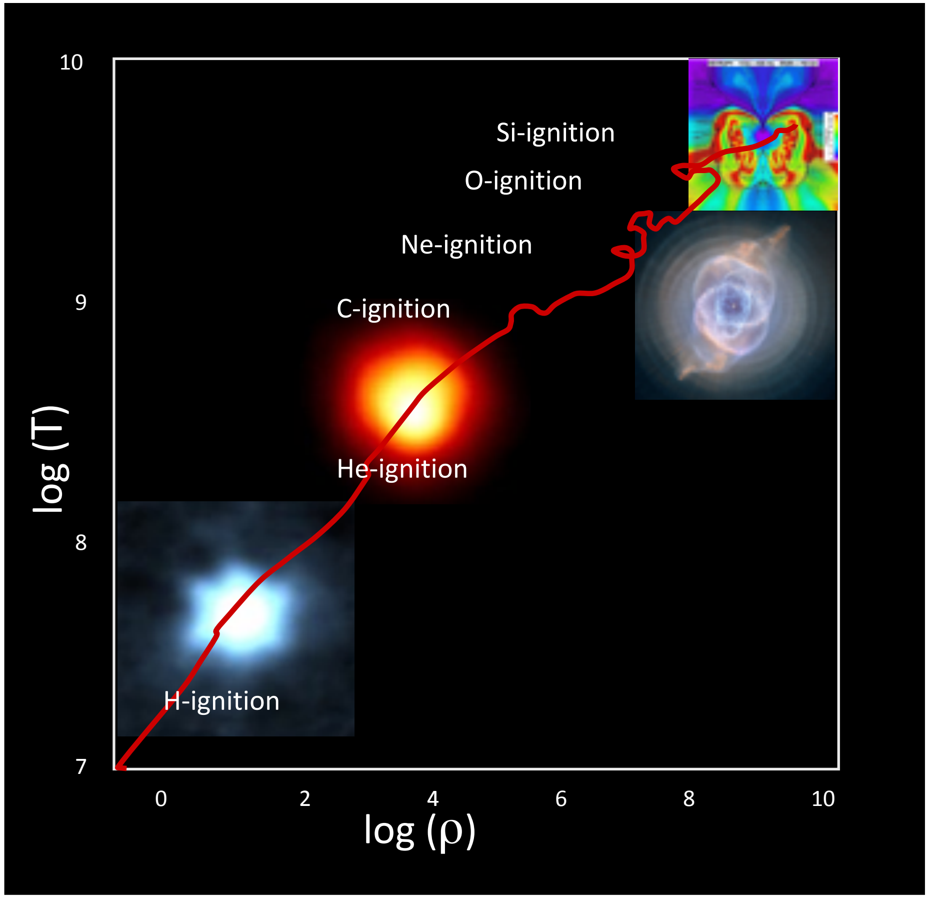
Nucleosynthesis in the Universe

- Protons and neutrons formed 10^{-6} s -1s after Big Bang (13.7 x 10^{9} years ago)
- H, D, He, Li, Be, B formed 3-20 min after Big Bang
- Other nuclei born later in heavy stars and supernovae



Nucleosynthesis and heavy-ion fusion



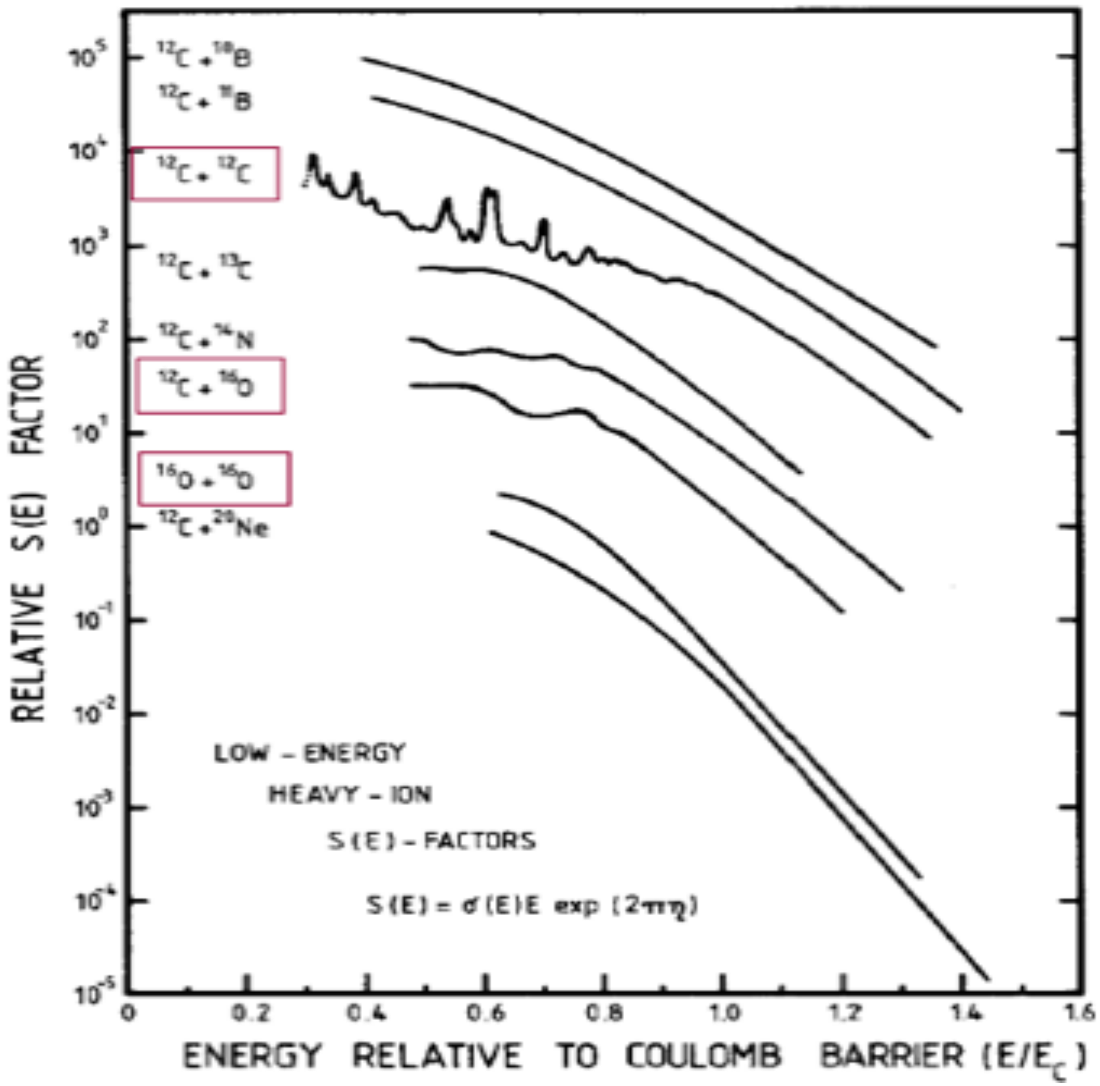
different burning phases characterize the evolution of a „massive“ star

↓

each burning phase is controlled by different nuclear reactions, which govern the:

- ➢ energy production
- ➢ time scale
- ➢ nucleosynthesis

The mystery of $^{12}C+^{12}C$



$^{12}C + ^{12}C$

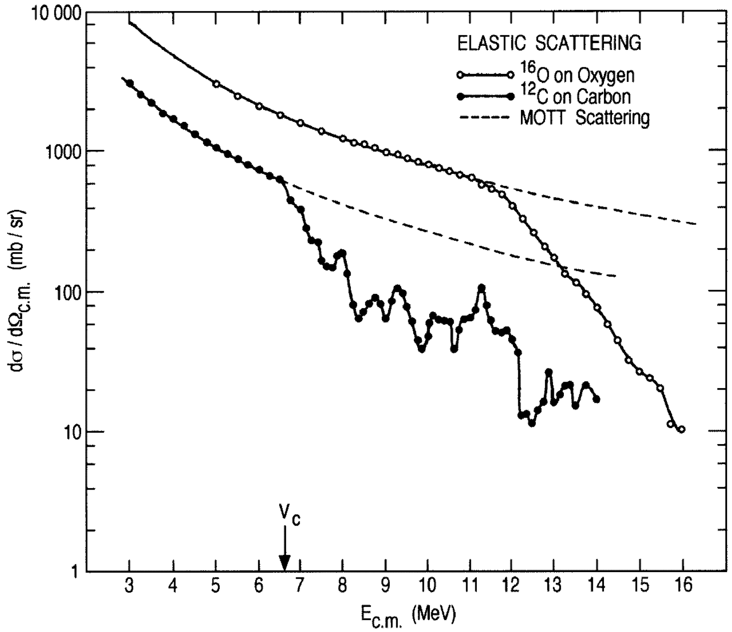


Figure 3. Excitation function data at $\theta_{cm} = 90°$ for $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ elastic scattering (Bromley *et al* 1960).

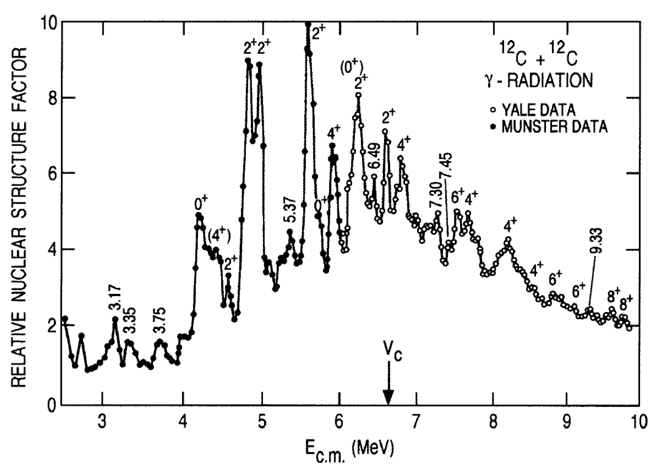


Figure 6. Deduced nuclear S factor for the $^{12}C + ^{12}C$ total reaction cross section (Erb and Bromley 1985).

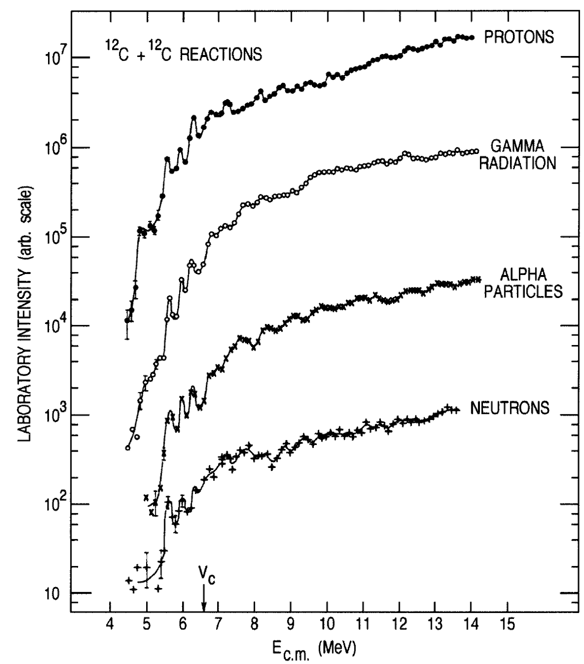
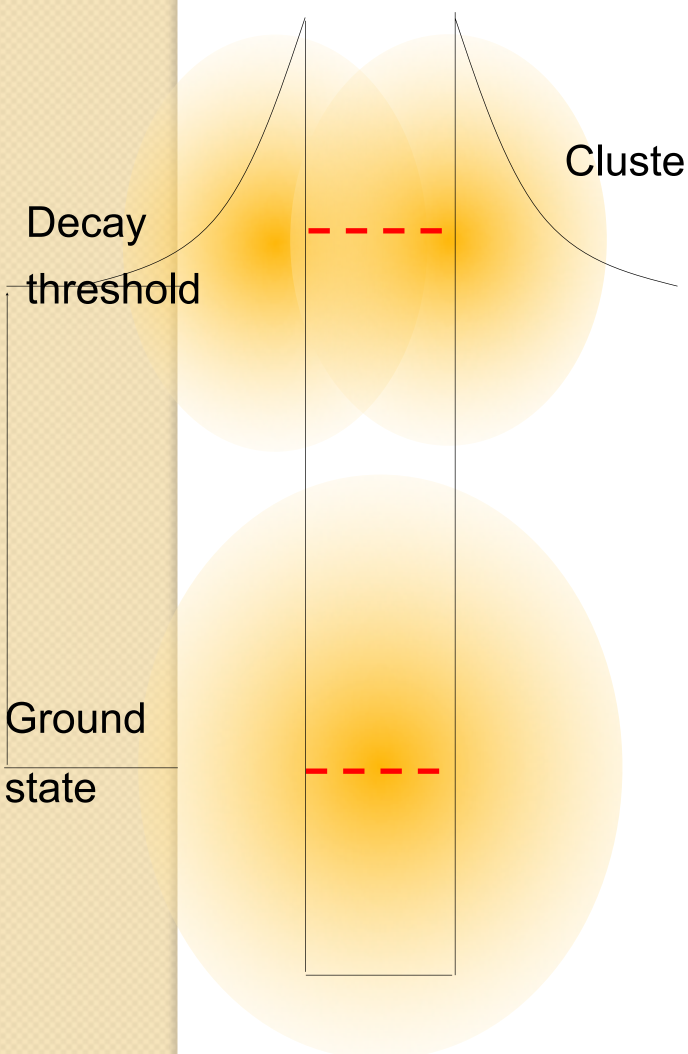
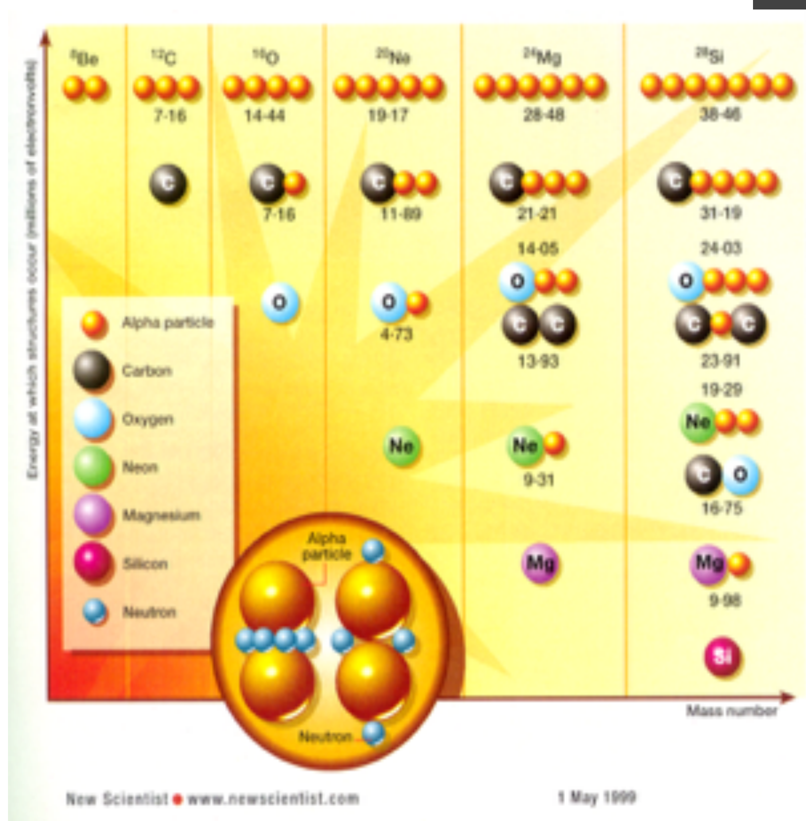


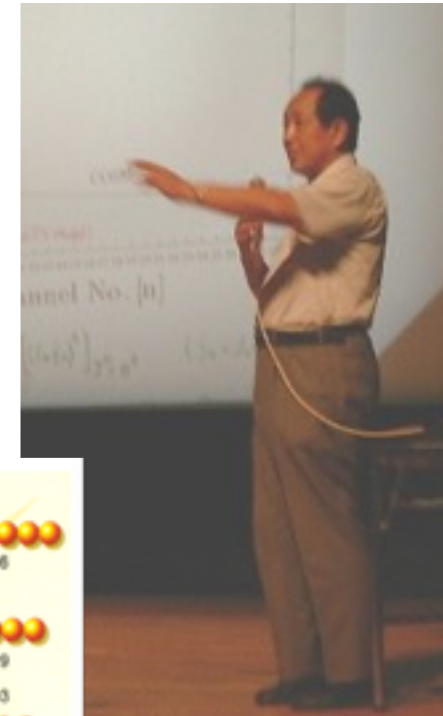
Figure 4. Reaction cross section data for $^{12}C + ^{12}C$ (Almqvist *et al* 1960) as a function of centre-of-mass bombarding energy. The arrow indicates the expected Coulomb barrier (V_C) for spherical ^{12}C nuclei.

Clustering may not appear in the ground state

Energetics



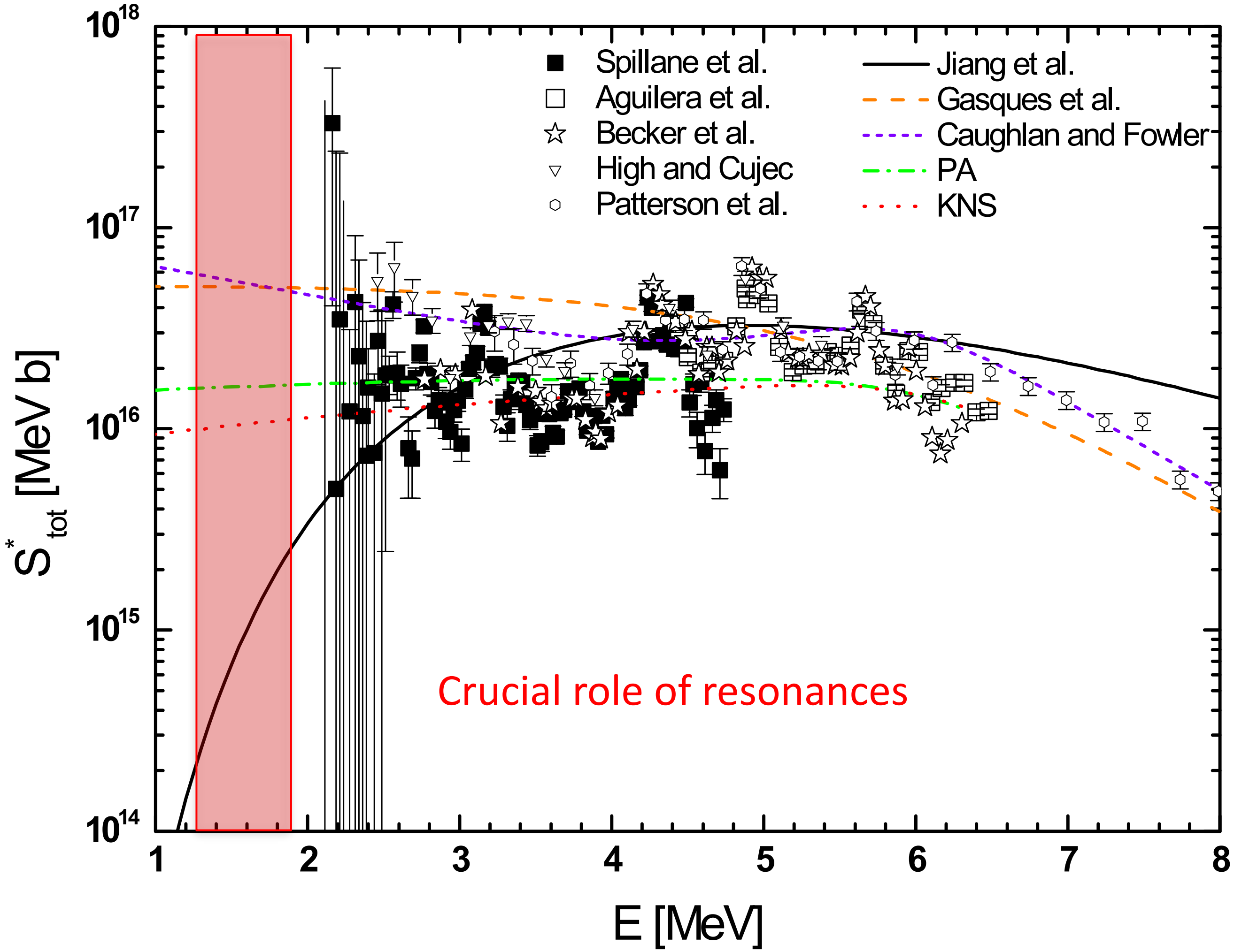




K. Ikeda, et al. Suppl. Prog. Phys. (Japan) Extra Nos. (1968) 464

$^{12}C+^{12}C$

Experimental investigations for this key reaction



$^{12}C + {}^{12}C$, experimental methods

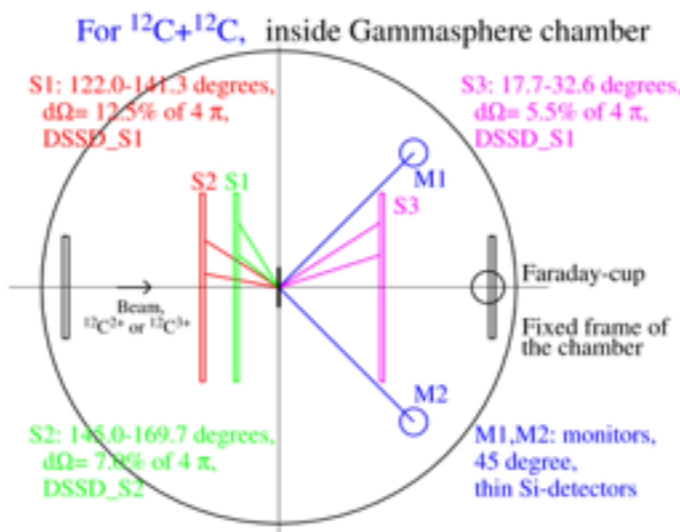
Particles **and** γ-rays

A new setup :
'Fusion measurements of $^{12}C+{}^{12}C$ at energies of astrophysical interest'
C.L. Jiang et al. (collab. ANL; IPHC, S. Courtin et al; CSNSM, A. Lefebvre-Schuhl)
Argonne National Laboratory, Chicago, USA
Atlas Tandem, ^{12}C, intense beam $E_{c.m.} = 3 – 5$ MeV

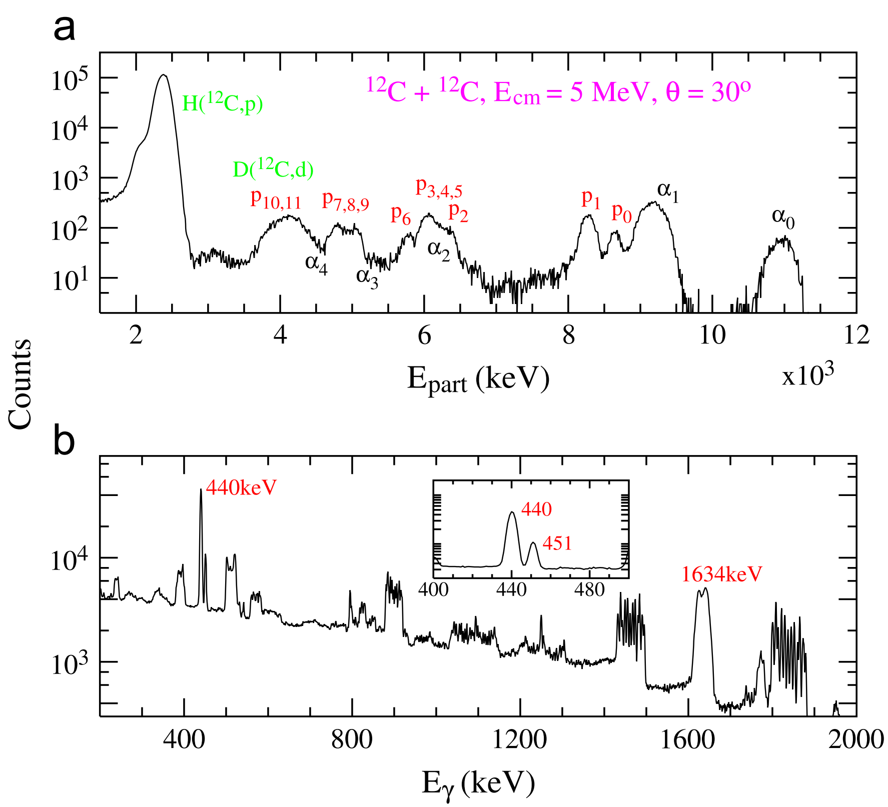
Detection system : coincidences γ + p and α

Gammasphere : 100 HPGe, e = 10%

Charged particles



$^{12}C+^{12}C$ fusion at ANL

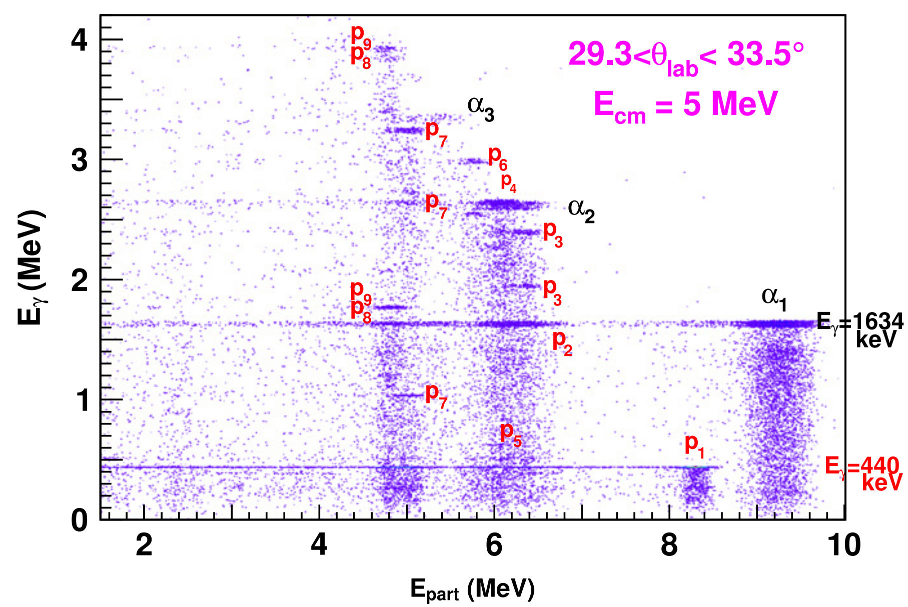


Particle-gamma measurement of $^{12}C+^{12}C$ at E_{cm} = 5 MeV

Relatively easy as cross-sections still quite large

Later measurements pushed down to E_{cm} ~ 3 MeV

Limit is beam current (100 pnA) and beam time



STELLA

Stellar Lab : a mobile experimental station for nuclear astrophysics and nuclear structure physics at future beam facilities

Collaboration: IPHC, IPNO, Univ. York (UK), Univ. Surrey (UK), GANIL, Univ. Aarhus (Denmark), Argonne National Laboratory (USA).

- **Physics** : heavy-ion fusion reactions in late stages of massive stars ($M > 8\ M_{solar}$).
  Gamma transitions between molecular resonances

Si

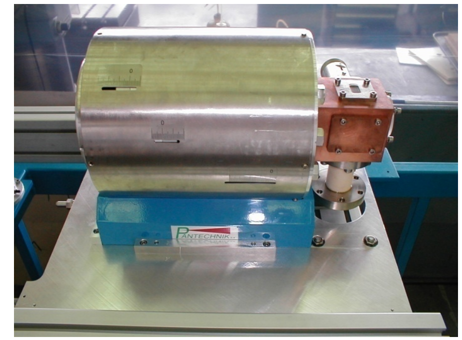
- **Systems** : $^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$.

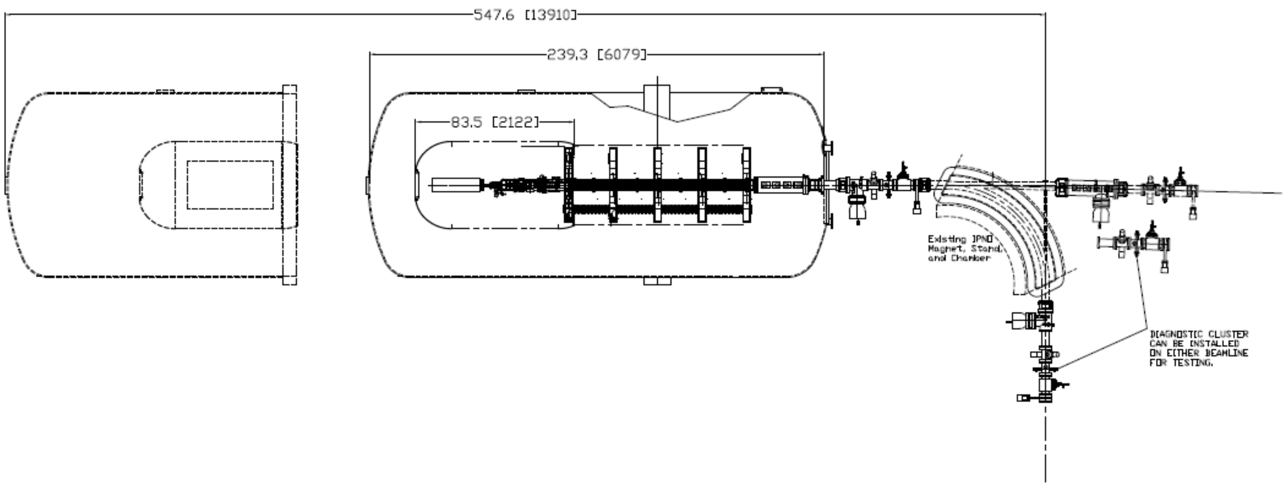
- **Impact** : nuclear molecules, nucléosynthesis, life cycle of stars, age of the Universe

- **Technique :** coincidences between particle and gamma-rays
  -> **low background measurement**

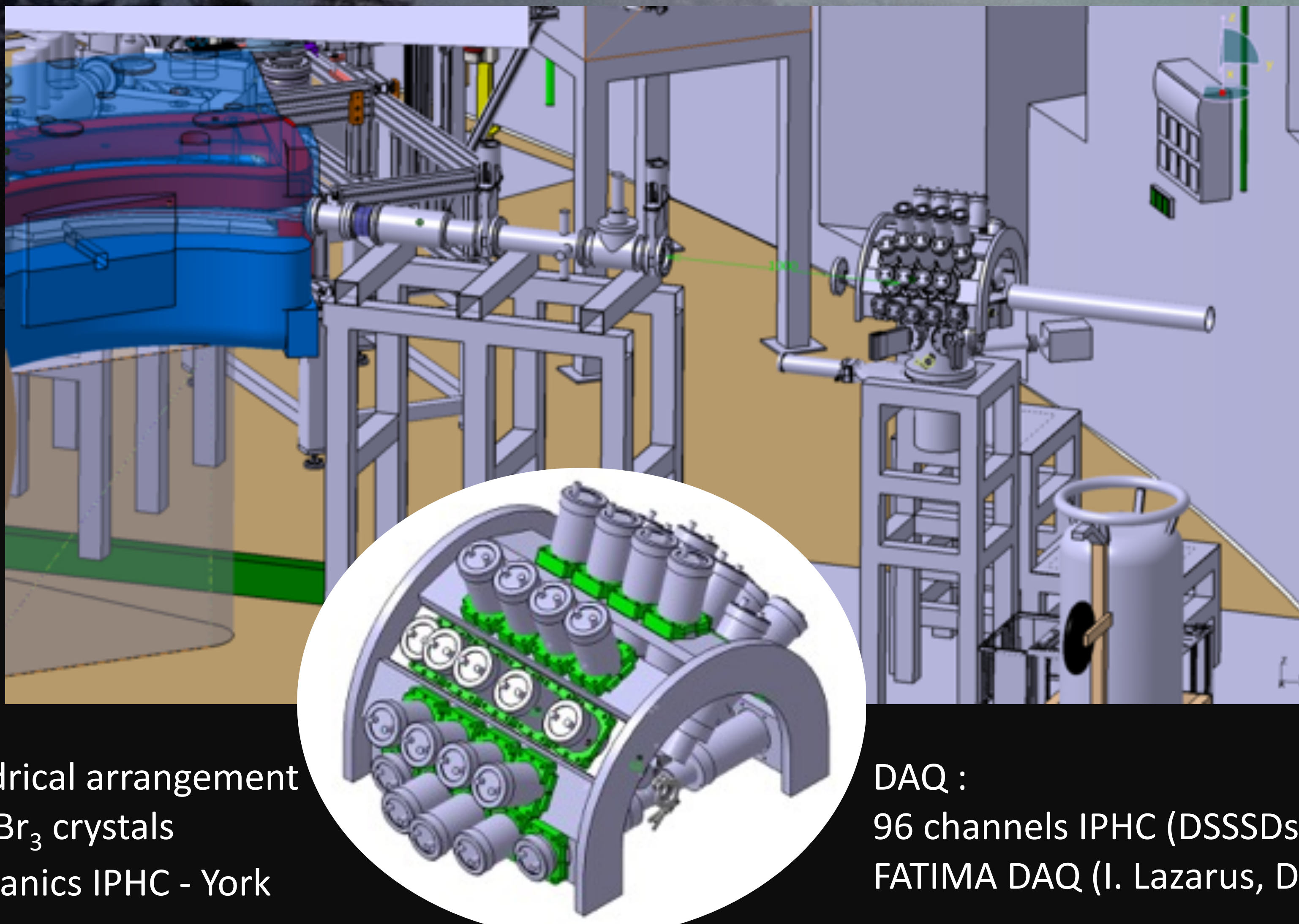
S. Courtin, D. Jenkins, G. Fruet, M. Heine, D. Montanari, F. Haas,
O. Kirsebom, G. Lotay,, P. Regan, F. Hammache, L. Morris,
S. della Negra, F. de Oliveira, N. de Séreville, C. Stodel et al

- 4 MV Van de Graaff Accelerator at IPN, Orsay (France)
- Commissioned Jan.-March 2016
- ^{12}C intensity: 5-10 μA
- Considerable beamtime available



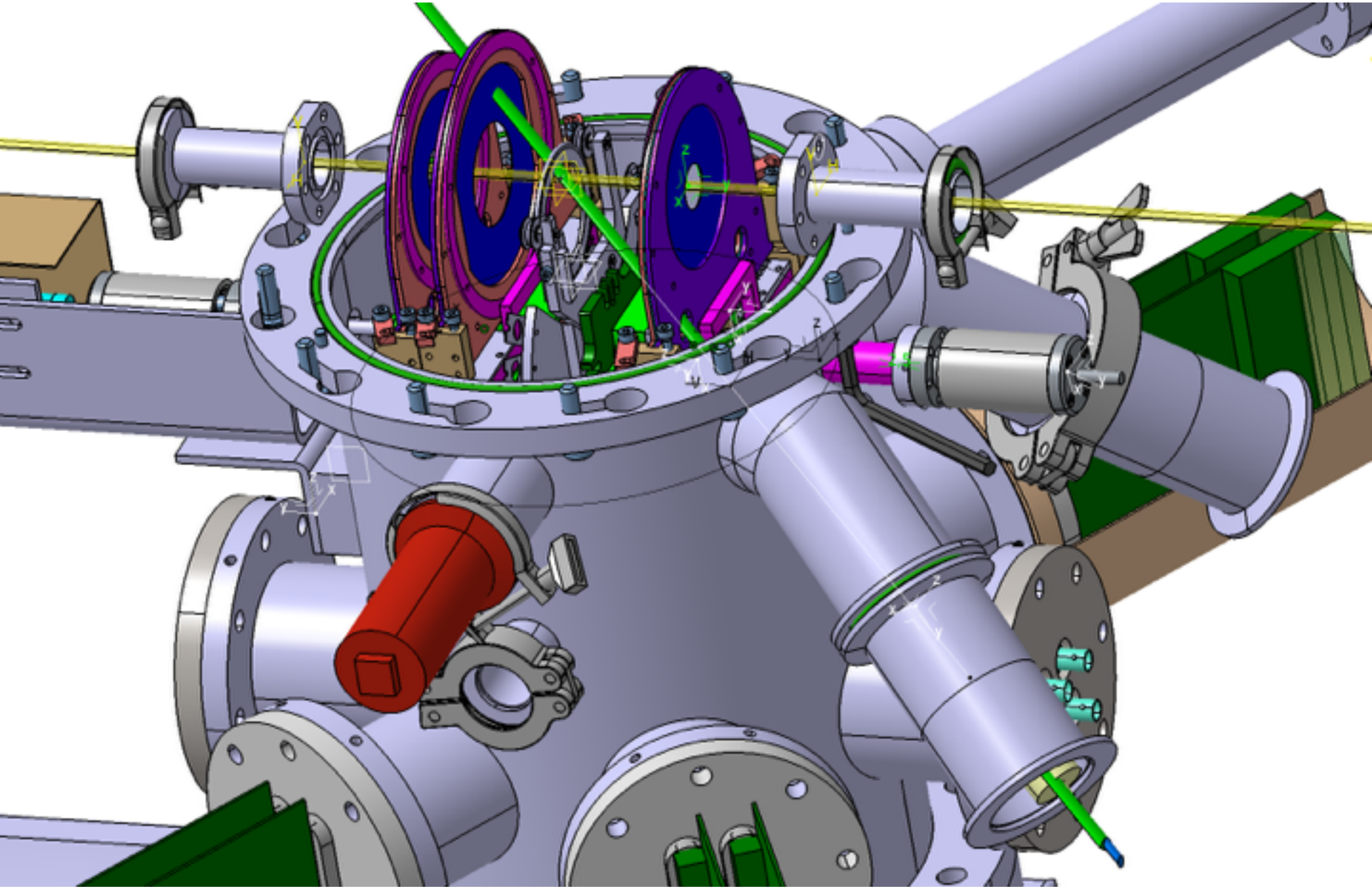


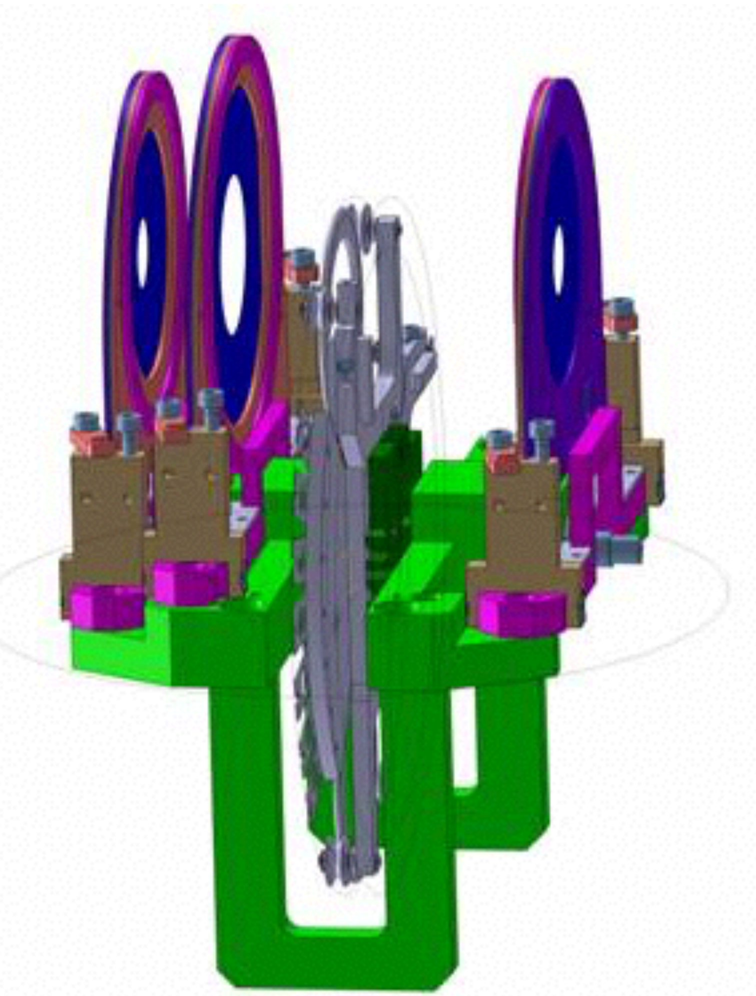
STELLA + FATIMA @ ANDROMEDE

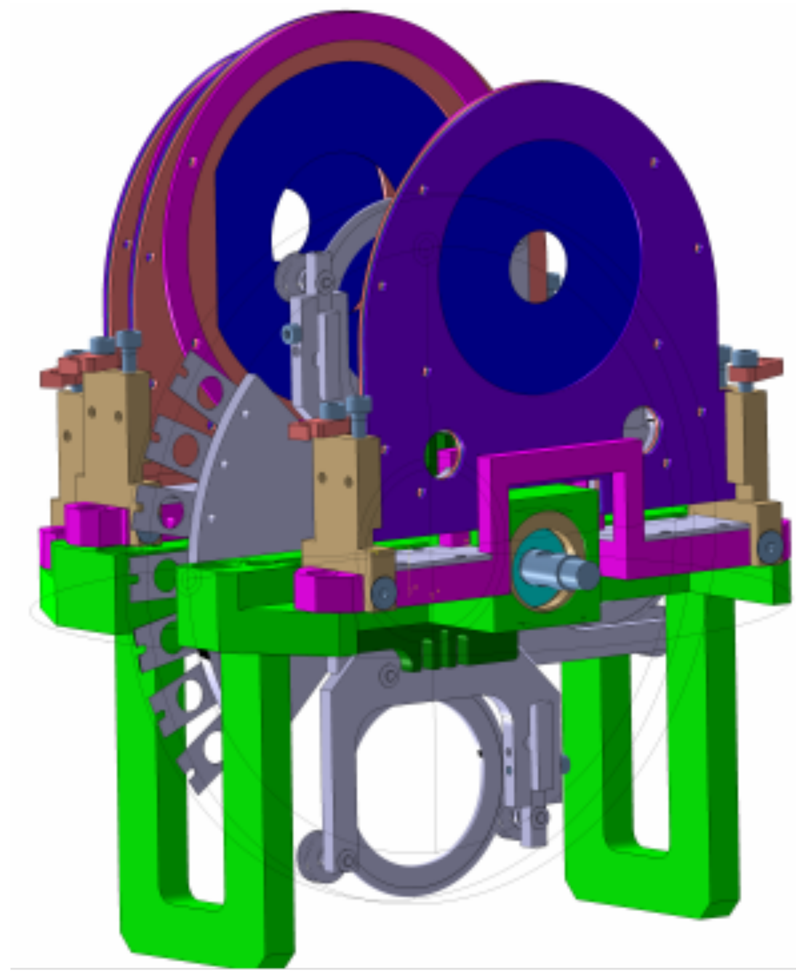


Cylindrical arrangement
36 $LaBr_3$ crystals
Mechanics IPHC - York

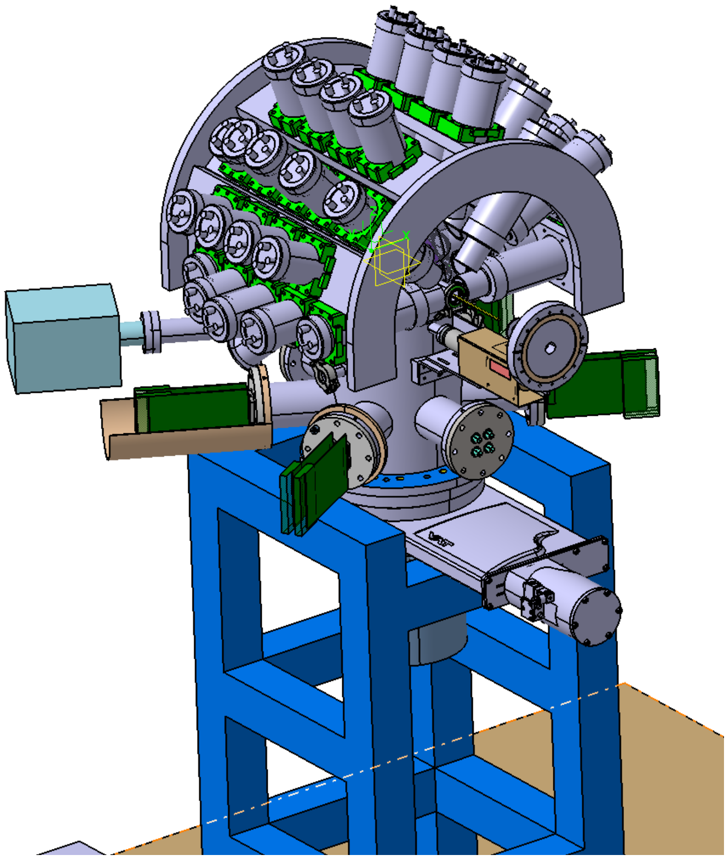
DAQ :
96 channels IPHC (DSSSDs)
FATIMA DAQ (I. Lazarus, Daresbury)

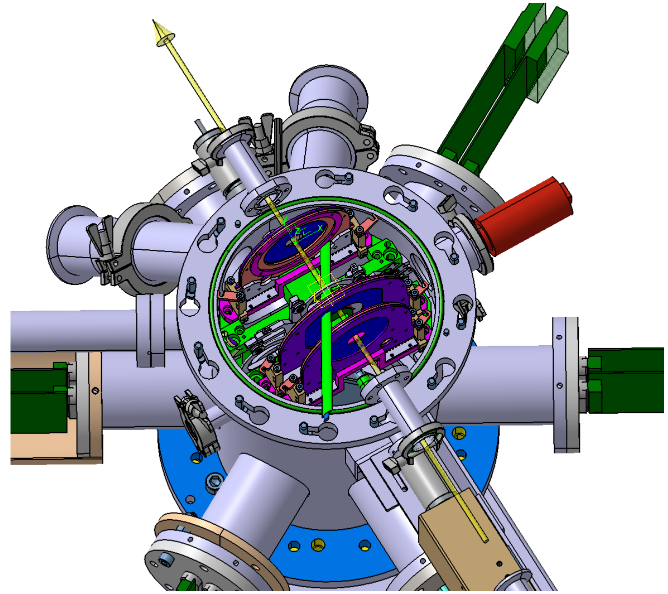


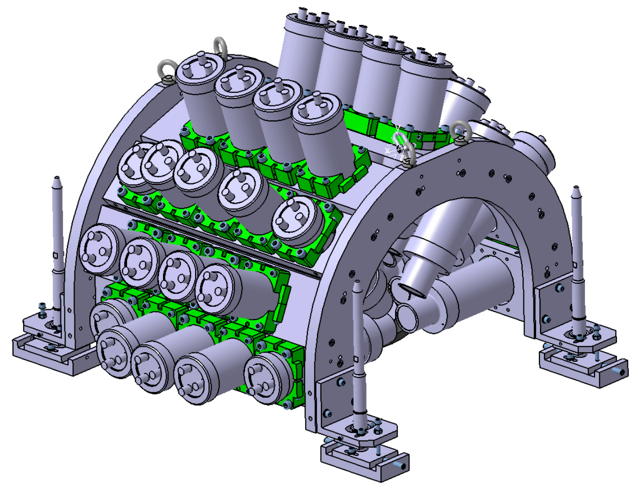




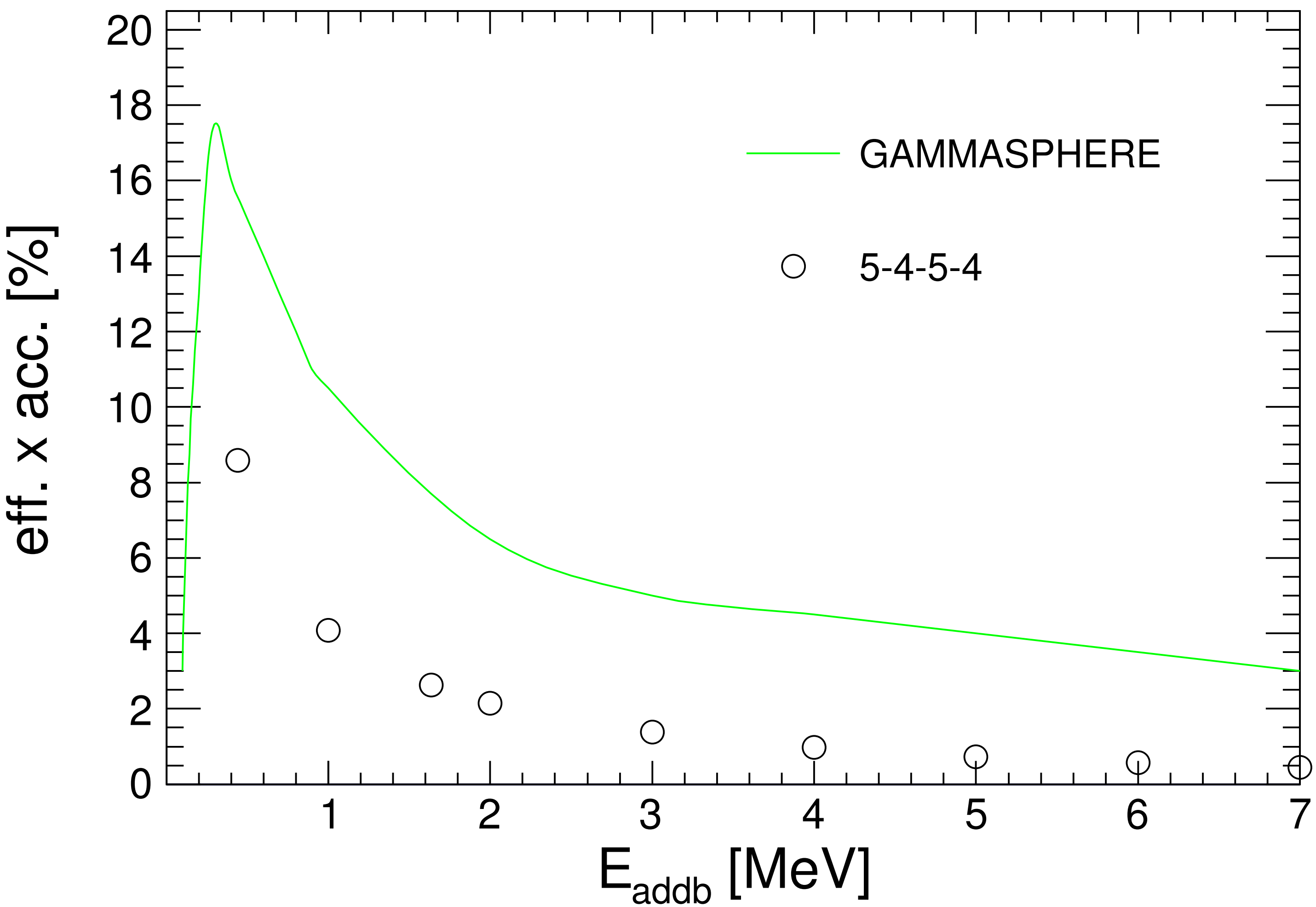
- Particles: 3 DSSSD
- Gammas: 36 $LaBr_3$







M. Krauth, P. Dene



Green: GAMMASHPERE, ANL

Circles: $LaBr_3$, STELLA

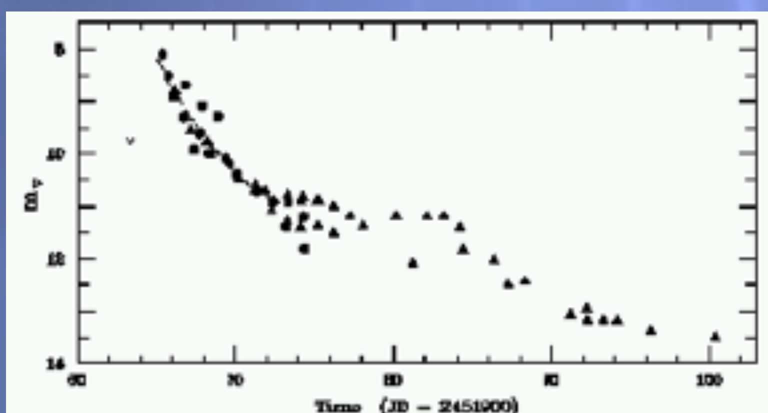
STELLA


STELLA-DAQ start
June 15
End Phase I-1
Dec 15
End Phase I-2
June 30
2016
2017
March
April
May
June
July
Aug
Sep
Oct
Nov
Dec
Jan
Feb
March
April
May
June
Irradiation tests
Angular distribution run
Test chamber
Mounting+tests
Reaction chamber
DAQ tests
Phase I-1
STELLA-FATIMA
$^{12}C + ^{12}C$
E_{lab} = 11 – 6 MeV
Rotating target system upgrade
Phase I-2
STELLA-FATIMA
High intensity Phase
$^{12}C + ^{12}C$
E_{lab} < 6 MeV

Other ideas for nuclear astrophysics and clustering with Nu-ball

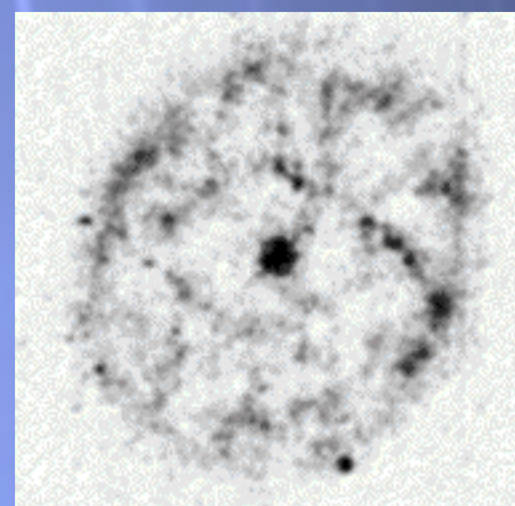
Constraints on nova models

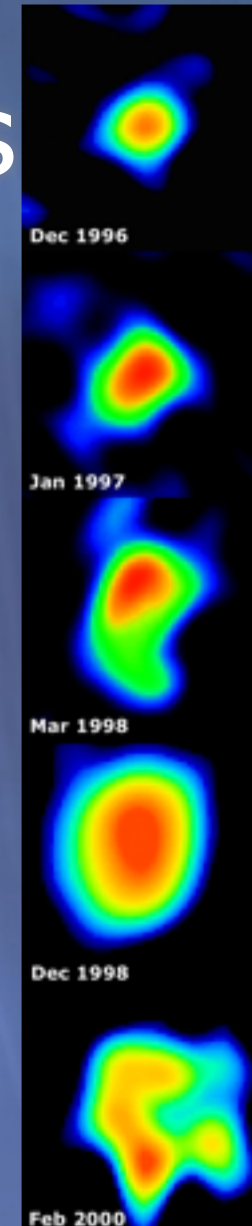
- Observational astronomy
  - Light output, time duration



Nova V4643 Sgr takes 4.8 days to decline 2 orders of mag

- Ejecta:
  - Dust grains
  - Cosmic gamma ray emitters: ^{22}Na, ^{26}Al





Cosmic gamma ray emitters

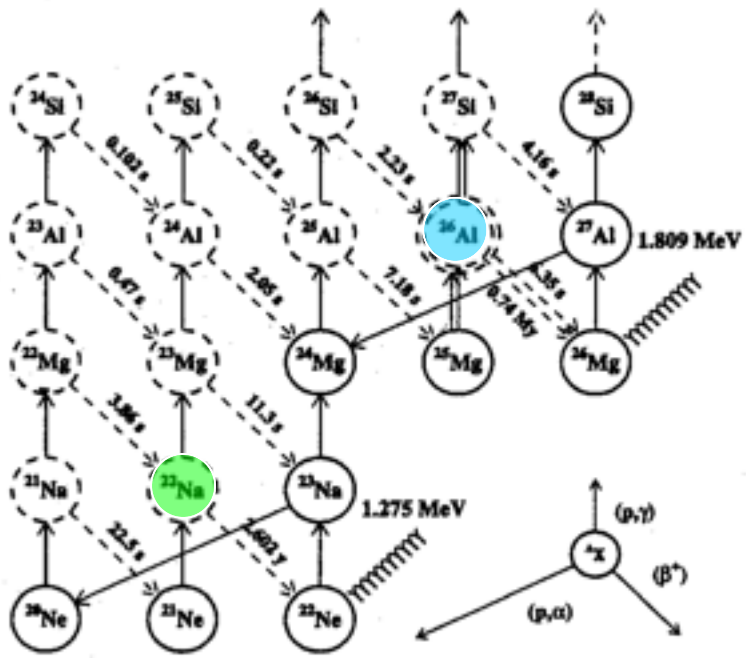


FIG. 2.—Main nuclear paths in both NeNa and MgAl cycles

Extended programme of study of sd-shell nuclei with Gammasphere

"Complete spectroscopy"

Detailed mirror symmetry information

Valuable data into nuclear reaction rates

PHYSICAL REVIEW C **89**, 045804 (2014)

Level structure of ^{31}S: From low excitation energies to the region of interest for hydrogen burning in novae through the ^{30}P(p,γ)^{31}S reaction

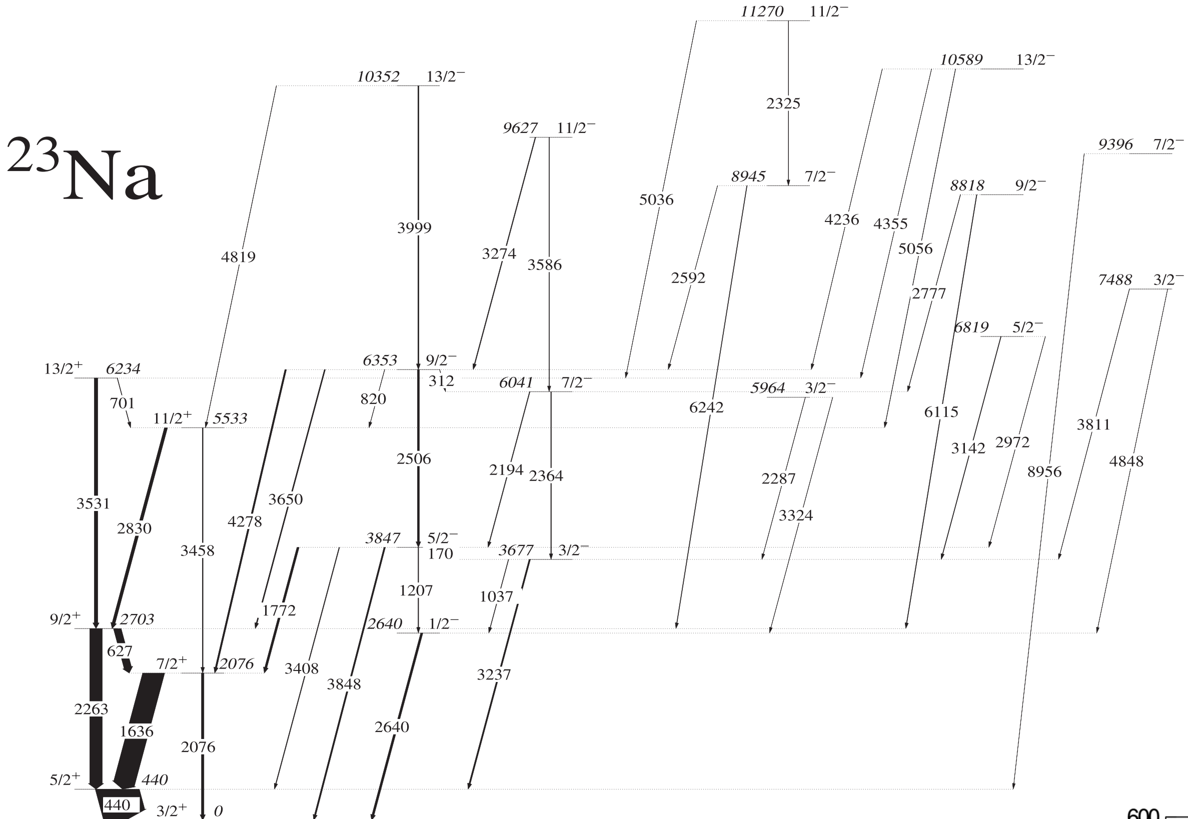
D. T. Doherty,[1,*] P. J. Woods,[1] G. Lotay,[1,†] D. Seweryniak,[2] M. P. Carpenter,[2] C. J. Chiara,[3,2] H. M. David,[1,‡] R. V. F. Janssens,[2] L. Trache,[4,§] and S. Zhu[2]
[1]*School of Physics and Astronomy, University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom*
[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*Department of Chemistry and Biochemistry, University of Maryland, College Park, Maryland 20742, USA*
[4]*Cyclotron Institute, Texas A&M University, College Station, Texas 77843, USA*
(Received 7 January 2014; revised manuscript received 14 March 2014; published 23 April 2014)

Comprehensive measurements of the excitation energy and spin-parity assignments for states in ^{31}S are presented, from the first excited state, up to energies relevant for the ^{30}P(p,γ)^{31}S reaction in ONe novae. This reaction rate strongly influences heavy element abundances in novae ejecta. States in ^{31}S are paired with their ^{31}P analogues using γ rays detected with the Gammasphere detector array following the ^{28}Si(^{4}He, n) fusion-evaporation reaction. The evolution of mirror energy differences is explored and the results are compared with new shell-model calculations. The excellent agreement observed in this work between experimental data and shell-model calculations provides confidence in using computed estimates in situations where experimental data are unavailable.

PHYSICAL REVIEW C **87**, 064301 (2013)

γ-ray spectroscopy of the $A = 23$, $T = 1/2$ nuclei ^{23}Na and ^{23}Mg: High-spin states, mirror symmetry, and applications to nuclear astrophysical reaction rates

D. G. Jenkins,[1,*] M. Bouhelal,[2] S. Courtin,[3] M. Freer,[4] B. R. Fulton,[1] F. Haas,[3] R. V. F. Janssens,[5] T. L. Khoo,[5] C. J. Lister,[5,†] E. F. Moore,[5] W. A. Richter,[6] B. Truett,[5] and A. H. Wuosmaa[5,‡]
[1]*Department of Physics, University of York, York YO10 5DD, United Kingdom*
[2]*Laboratoire de Physique Appliquée et Théorique, Université de Tébessa, Tébessa, Algeria*
[3]*IPHC, Université de Strasbourg, CNRS-IN2P3, Strasbourg, France*
[4]*School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, United Kingdom*
[5]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[6]*iThemba Labs, P.O. Box 722, Somerset West 7129, South Africa and Department of Physics, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa*
(Received 27 March 2013; published 4 June 2013)



^{23}Na
11270 11/2−
10589 13/2−
10352 13/2−
9627 11/2−
9396 7/2−
8945 7/2−
8818 9/2−
7488 3/2−
6819 5/2−
13/2+ 6234
6353 9/2−
6041 7/2−
5964 3/2−
11/2+ 5533
3847 5/2−
3677 3/2−
9/2+ 2703
2640 1/2−
7/2+ 2076
5/2+ 440
3/2+ 0
2325
5036
4819
3999
3274
3586
2592
4236
4355
5056
2777
6242
6115
312
820
701
3531
2830
3458
4278
3650
2506
2194
2364
2287
3324
3142
2972
8956
3811
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1207
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1772
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2263
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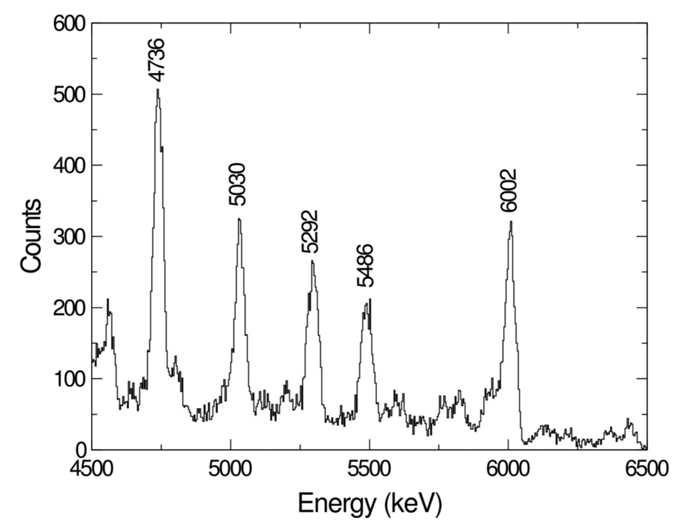
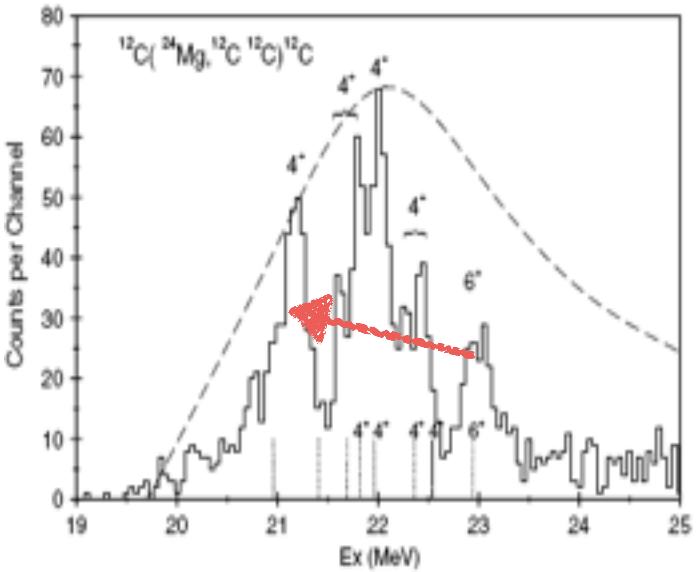
2076
3408
3848
2640
3237
440



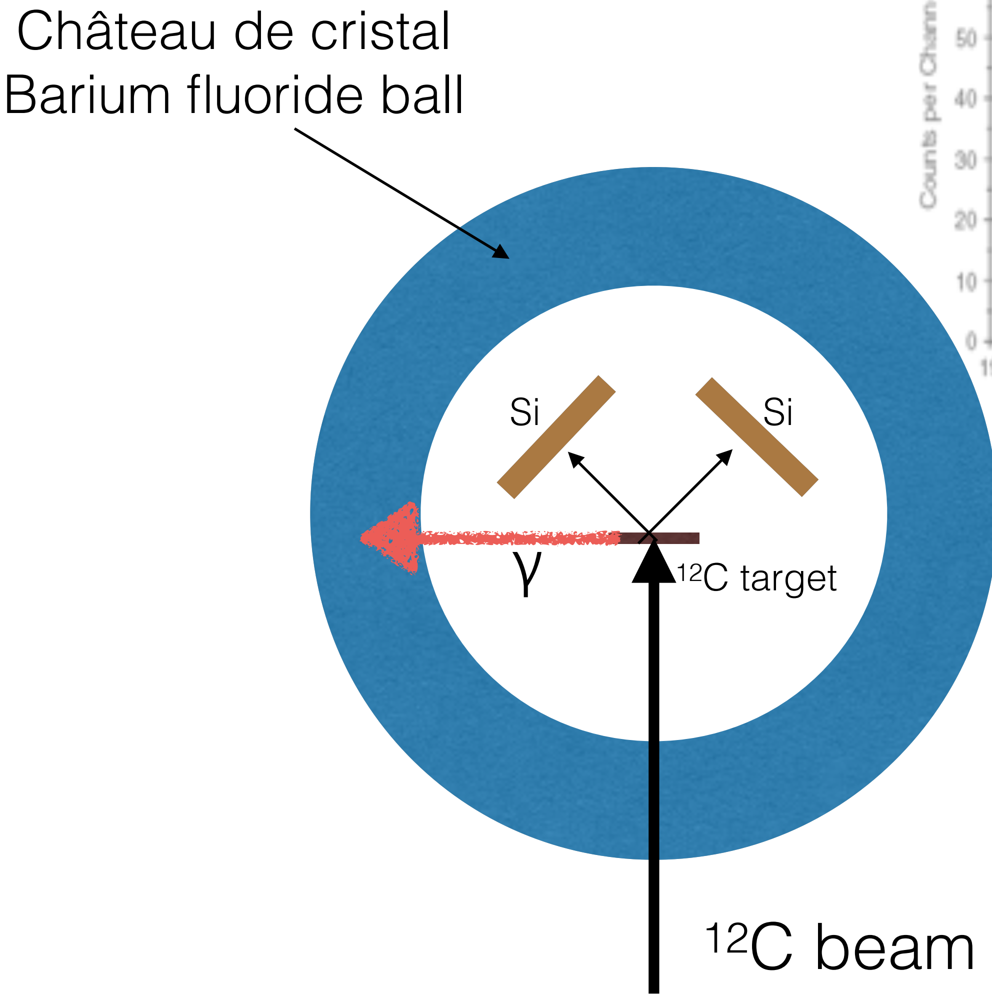
Counts
Energy (keV)
4736
5030
5292
5486
6002
0
100
200
300
400
500
600
4500
5000
5500
6000
6500

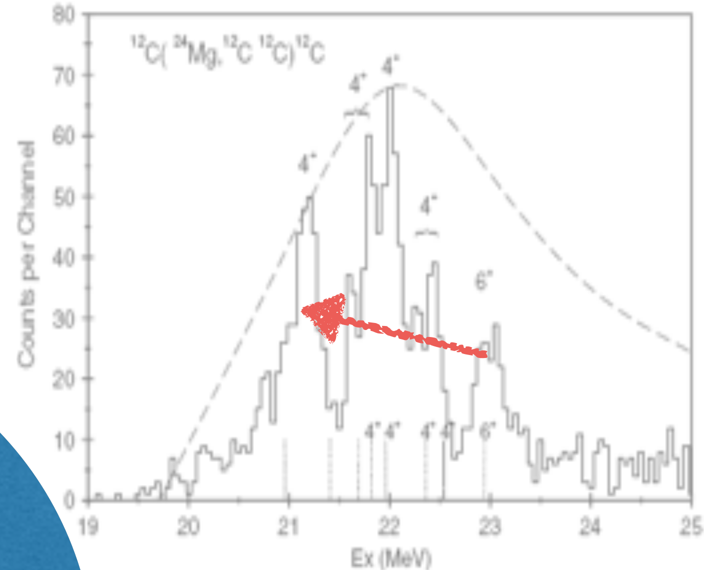
Are there EM transitions between $^{12}C+^{12}C$ molecular resonances?

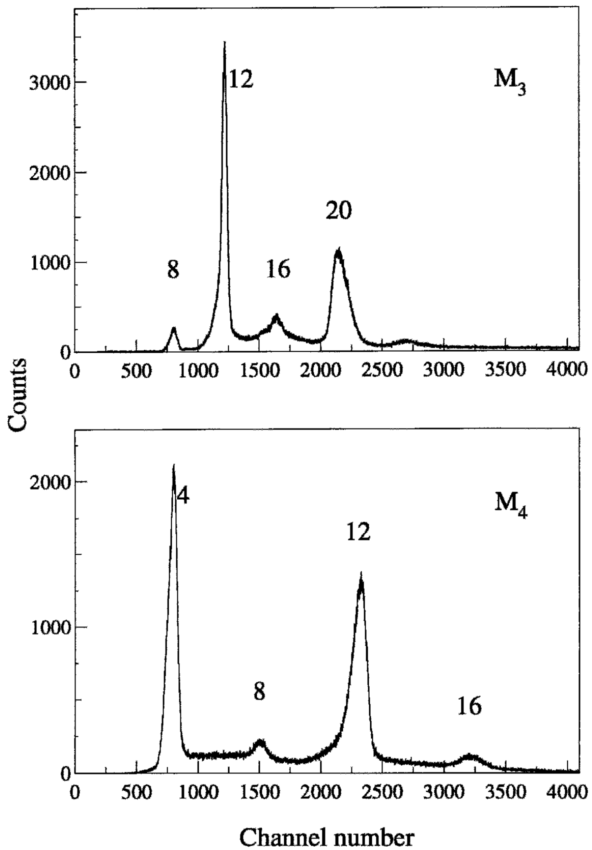


Perspective:

1) Transitions should be strong - B(E2) ~ 100s Wu.
2) Gamma width ~ eV, break-up width 100 keV -> Gamma branch ~ 10^{-5}
3) Gamma decay will be split between many different final states (resonances)


Château de cristal
Barium fluoride ball
Si
Si
γ
12C target
12C beam


12C(24Mg,12C 12C)12C
Counts per Channel
Ex (MeV)
4+
4+
4+
4+
4+
6+
4+ 4+ 4+ 4+ 6+
0
10
20
30
40
50
60
70
80
19
20
21
22
23
24
25



F. Haas et al.,
Il Nuovo Cimento A110, 989 (1997)

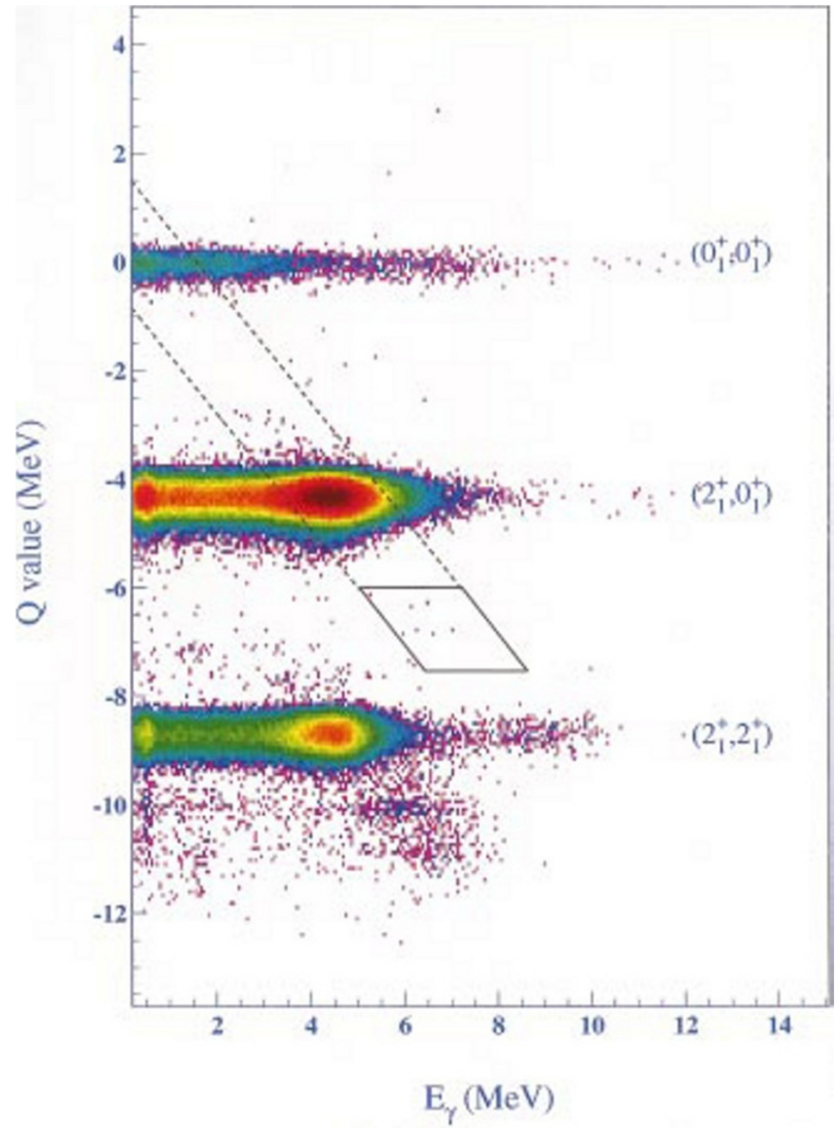


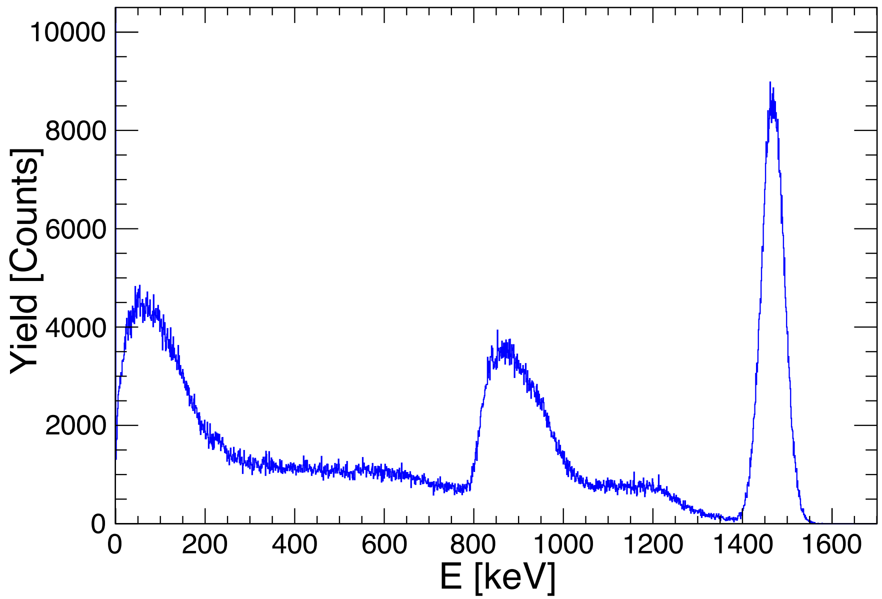
Fig. 4. – Reaction Q-value of the $^{12}C(^{12}C, ^{12}C)^{12}C$ reaction at $E_{lab} = 32.9$ MeV *vs*. the fragment γ-ray energies E_γ. The spectrum has been obtained with the fragment-fragment-γ coincidence condition and a γ multiplicity $M_\gamma = 1$ condition (see text).

Spare slides

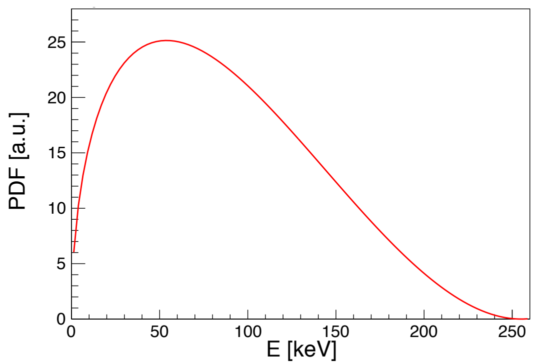
$$T_{1/2} = 1.05 \cdot 10^{11} \text{ a, nat. ab.} = 0.090\% \Rightarrow A = 90 \text{ Bq}$$

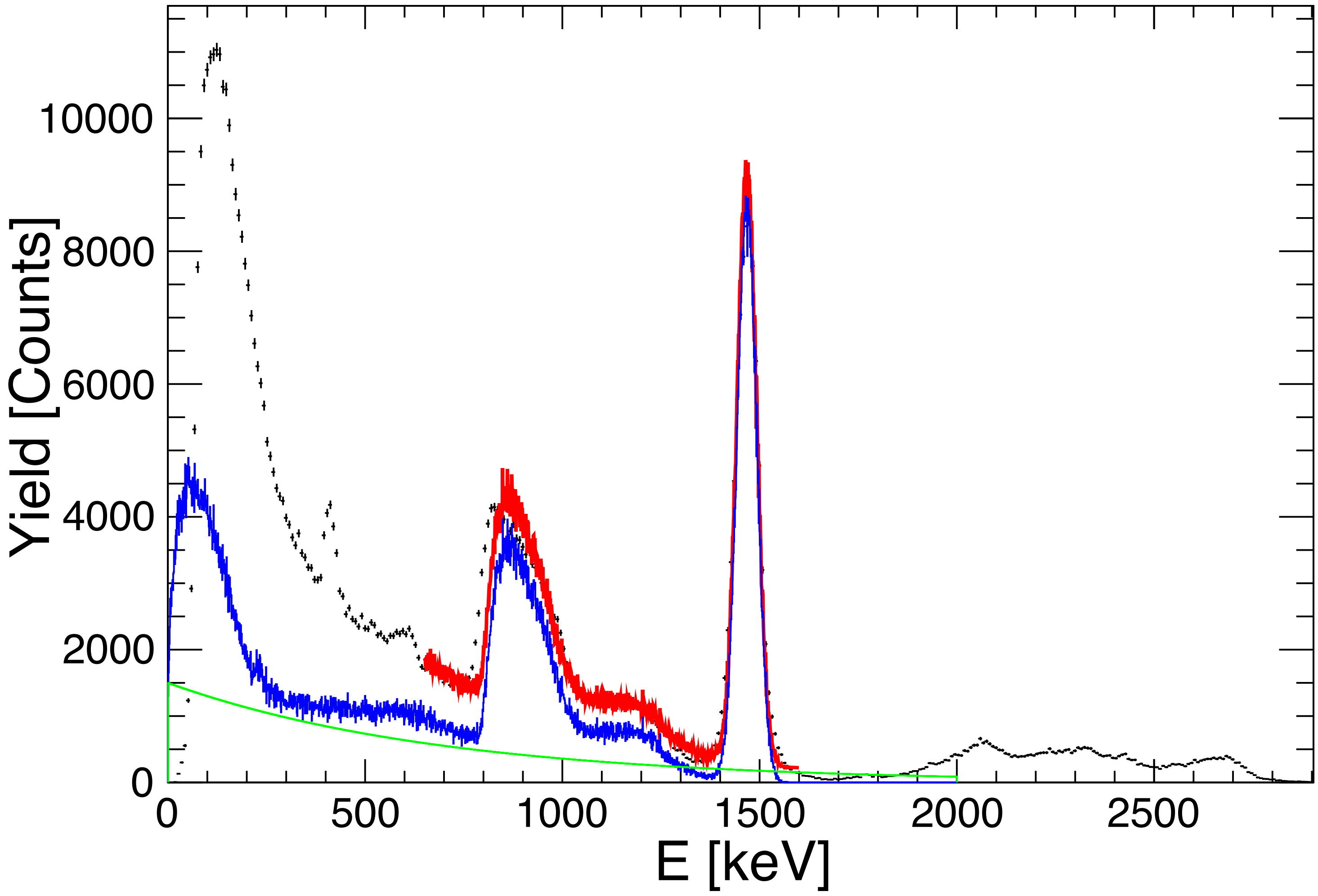
$$66\% : {}^{138}\mathrm{La} + \mathrm{e}^- \rightarrow {}^{138}\mathrm{Ba} + \bar{\nu}_\mathrm{e};\ E_\gamma = 1.436 \text{ MeV}$$

$$34\% : {}^{138}\mathrm{La} \rightarrow {}^{138}\mathrm{Ce} + \mathrm{e}^- + \nu_\mathrm{e};\ E_\gamma = 0.789 \text{ MeV}$$



Beta decay Spectrum





Green: exponential background

Blue: simulation

γ transitions between molecular resonances:

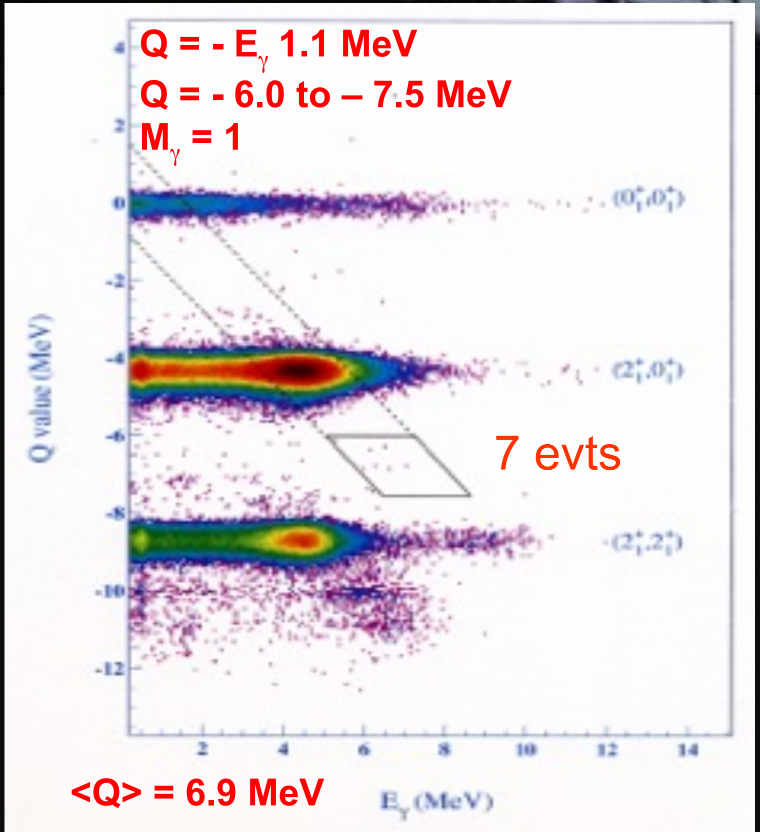
Electromagnetic transitions between $^{12}C+^{12}C$ resonant states as a probe for clustering in ^{24}Mg

1^{st} attempt, Haas et al. (1997)

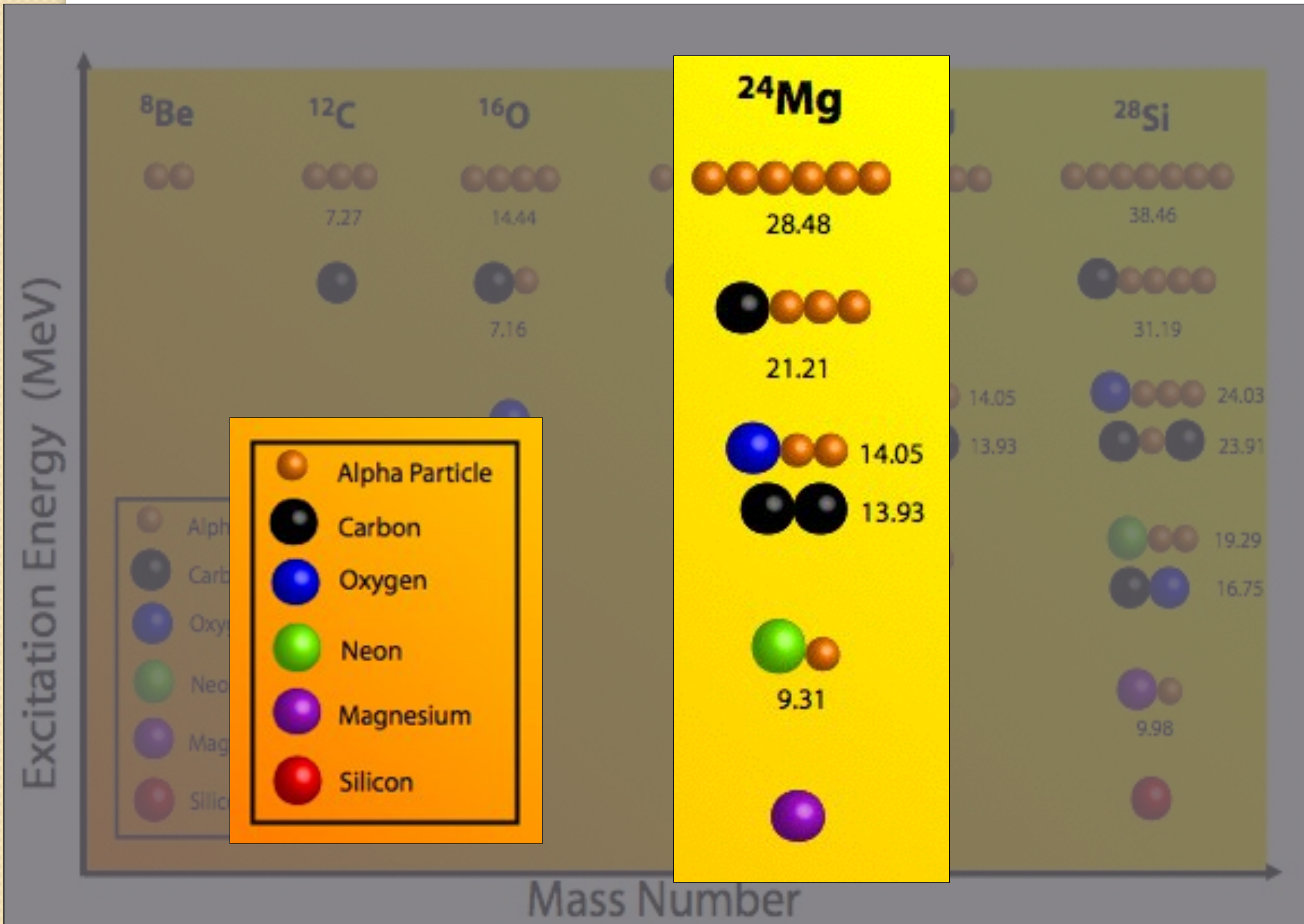
$^{12}C+^{12}C$, Orsay Tandem, I_{12C} = 5 pnA

Chateau de Cristal + 2 PSD detectors, 5 days experiment, 7 events

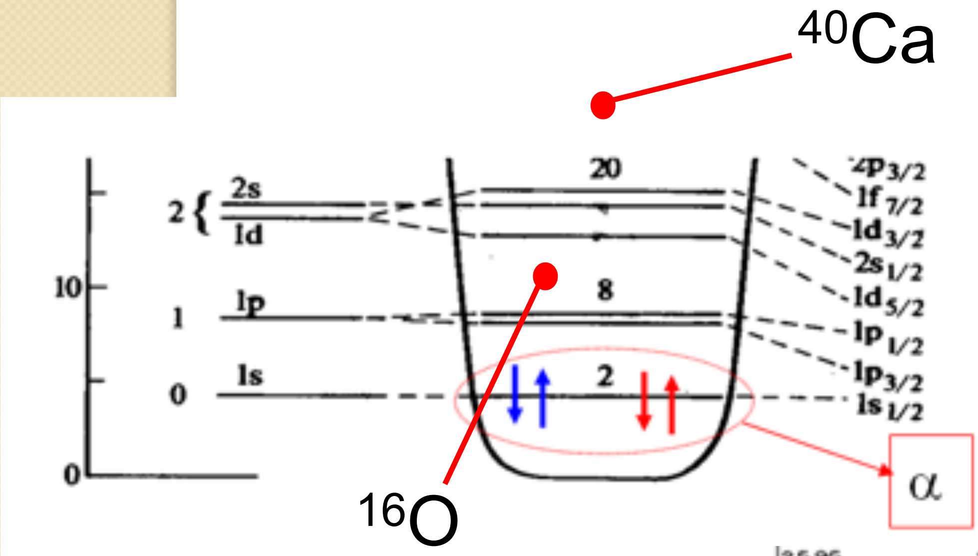
Low beam intensity + ^{12}C and ^{16}O contamination …



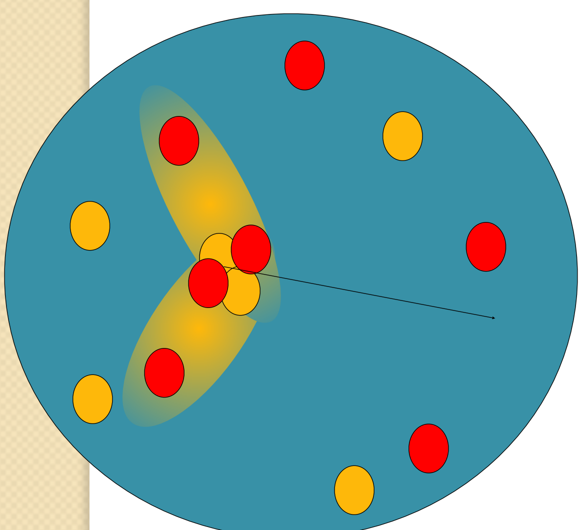
Ikeda Diagram

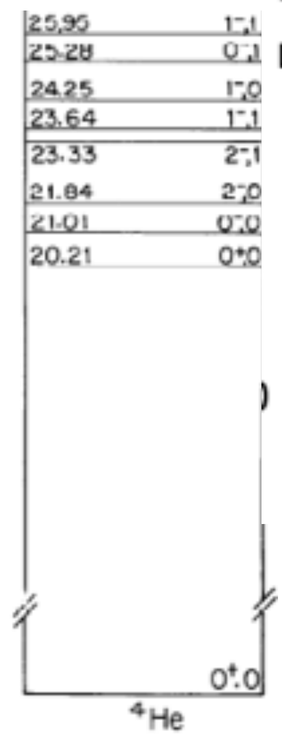


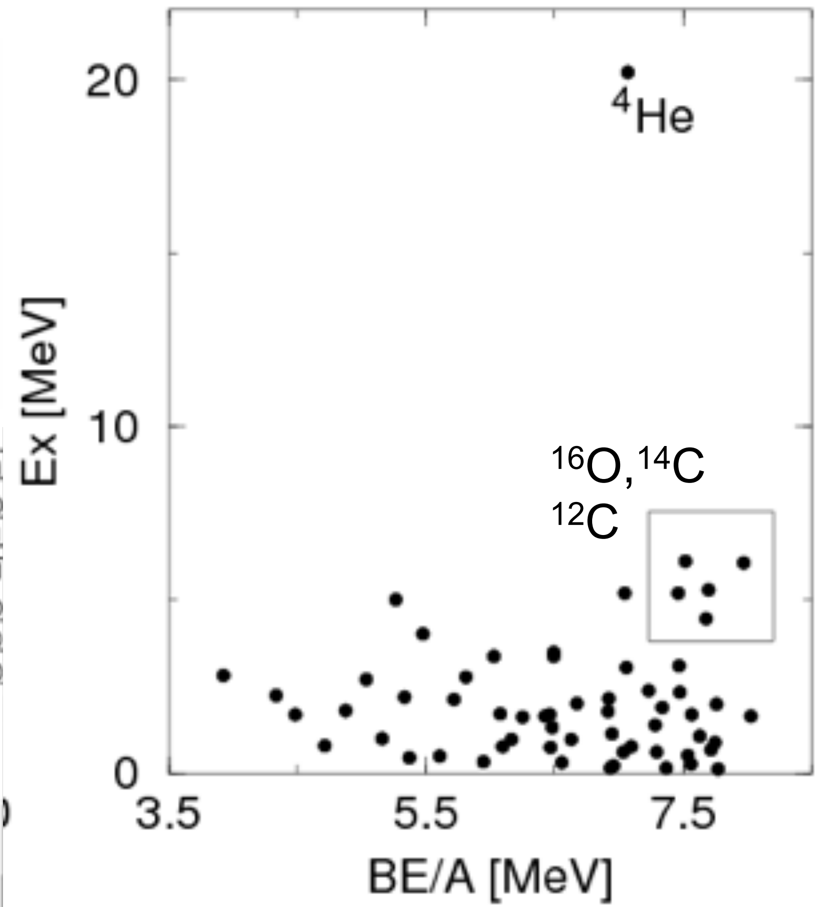
Good clusters might be those which have maximally correlated nucleons = closed shell nuclei



How robust is the Cluster?

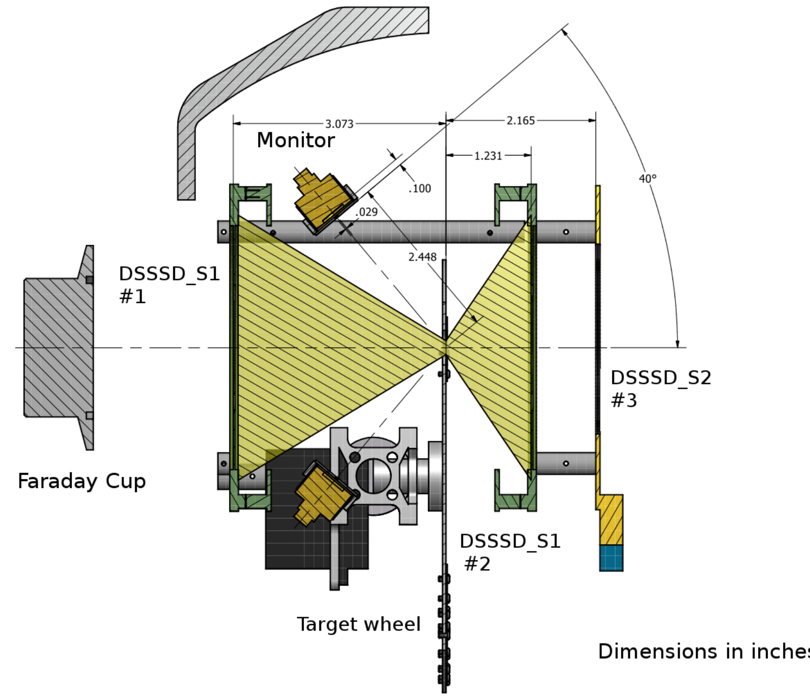


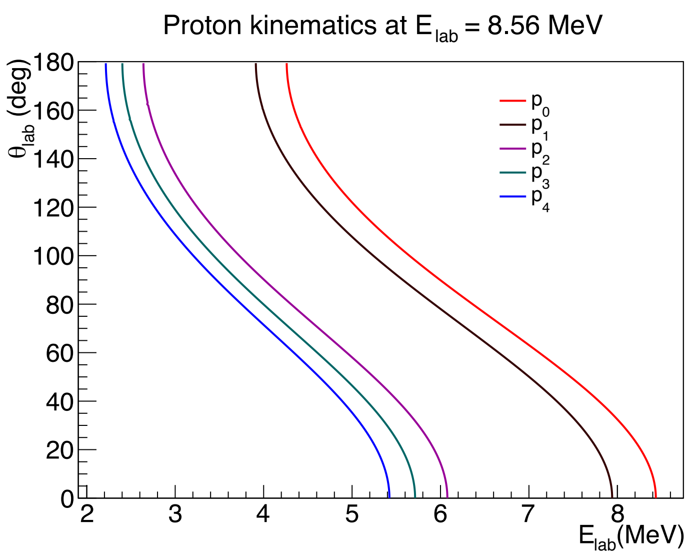


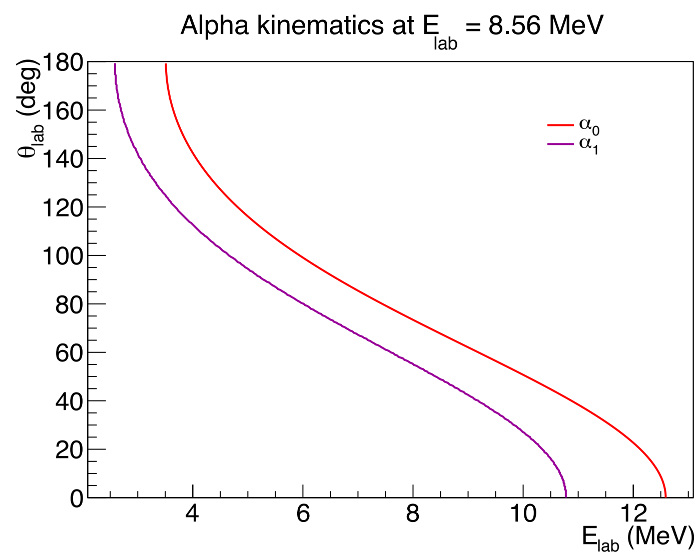


The alpha-particle is "King Cluster"

$^{12}C+^{12}C$ fusion at ANL







Red giant phase