Symposium in Honor of Nikola Cindro
"Highlights in Heavy-Ion Physics"
Sep 22-24, 2011, Split, Croatia

Zagreb initiative on research in nuclear astrophysics

or

Can small nuclear physics group from small country survive the crisis ?

Neven Soić, Ruđer Bošković Institute, Zagreb, Croatia

FP7 REGPOT,
Start May 2008, End: July 2011

Clustering phenomena in nuclear physics: strengthening of the Zagreb–Catania–Birmingham partnership

http://lnr.irb.hr/cluna

Partners

- Ruđer Bošković Institute – coordinator
- University of Zagreb
- University of Birmingham, UK
- INFN – Laboratori Nazionali del Sud Catania, Italy

Funding: 370,000 €
Equipment ~ 35 % total
Upgrade of experimental beam line at the RBI Tandem
New PhD student position
Travelling – exchange of knowledge and experience, practical trainings

Equipment
Si detectors: SSSD thin 20 μm, DSSSD and PSD
Neutron detectors- EJ-309
Electronics, VME DAQ units

FP7 REGPOT,
Start August 2010

Upgraded Facility for Development of Silicon and Diamond Particle Detector Systems

http://lnr.irb.hr/pd

- 3 largest laboratories of the Division of Experimental Physics

•Laboratory for ion beam interactions
•Laboratory for nuclear physics
•Laboratory for high energy physics

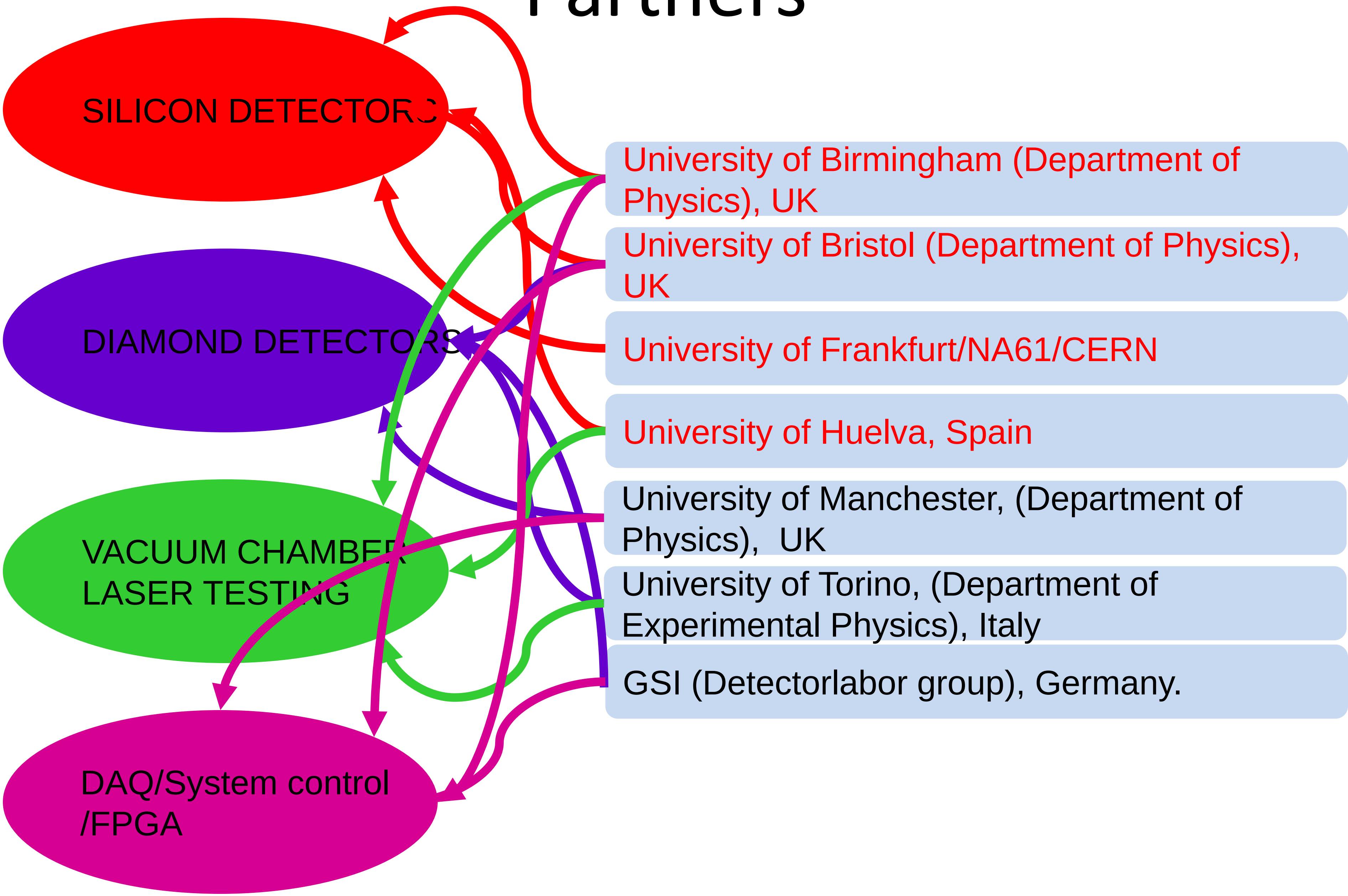
~33 employees,
15 directly included

All three laboratories participate in WP2
Development of novel detector arrays
LIBI – strip, PSD
LNP- strip, PSD, pixel
LHEP – strip, pixel

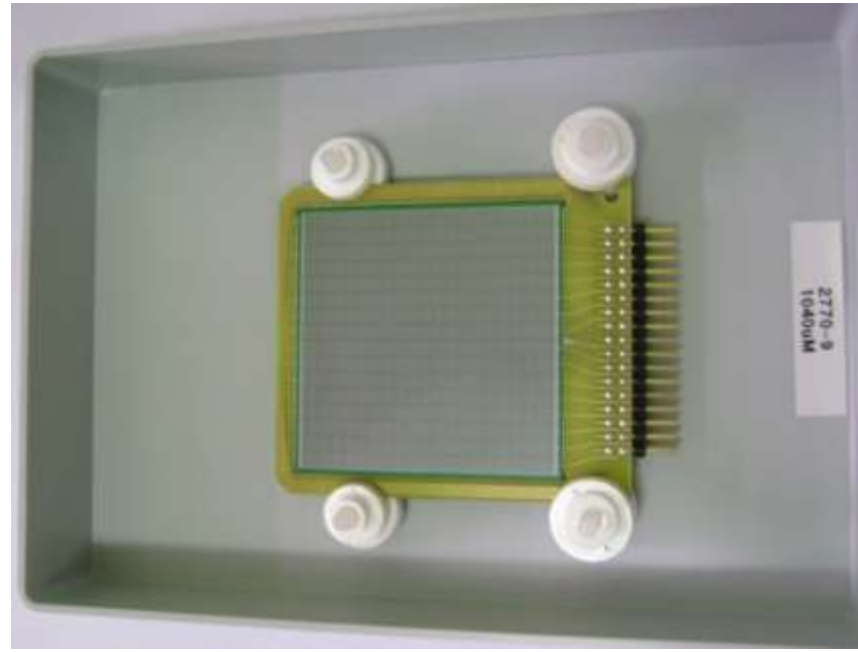
Funding: 1,319,538 €
silicon part: 405,156 €

Equipment ~ 35 % total
New postdoc position
Travelling – exchange of knowledge and experience, practical trainings

Partners



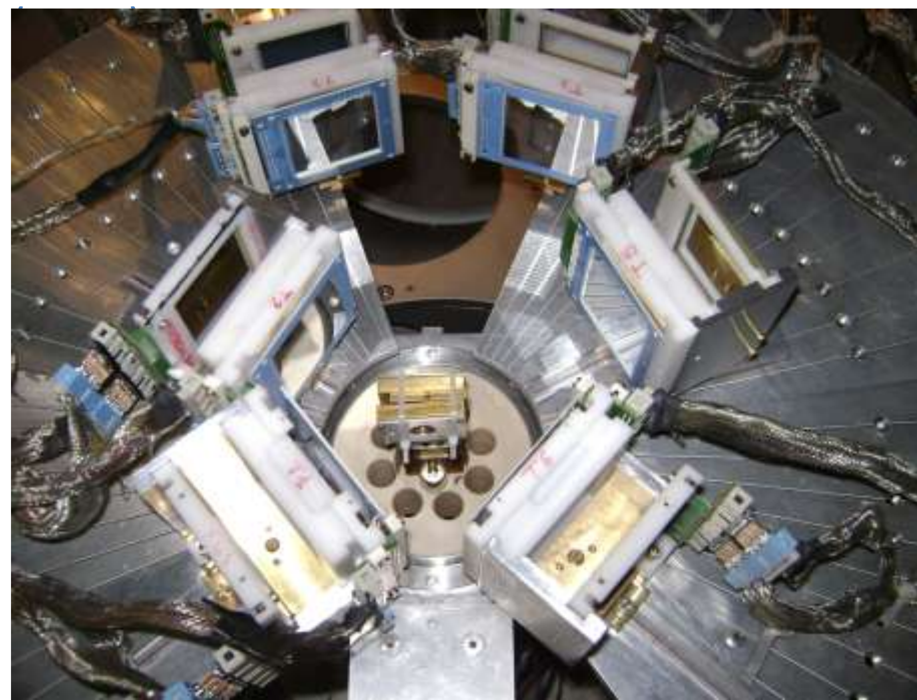
SILICON DETECTORS
DIAMOND DETECTORS
VACUUM CHAMBER
LASER TESTING
DAQ/System control
/FPGA
University of Birmingham (Department of Physics), UK
University of Bristol (Department of Physics), UK
University of Frankfurt/NA61/CERN
University of Huelva, Spain
University of Manchester, (Department of Physics), UK
University of Torino, (Department of Experimental Physics), Italy
GSI (Detectorlabor group), Germany.

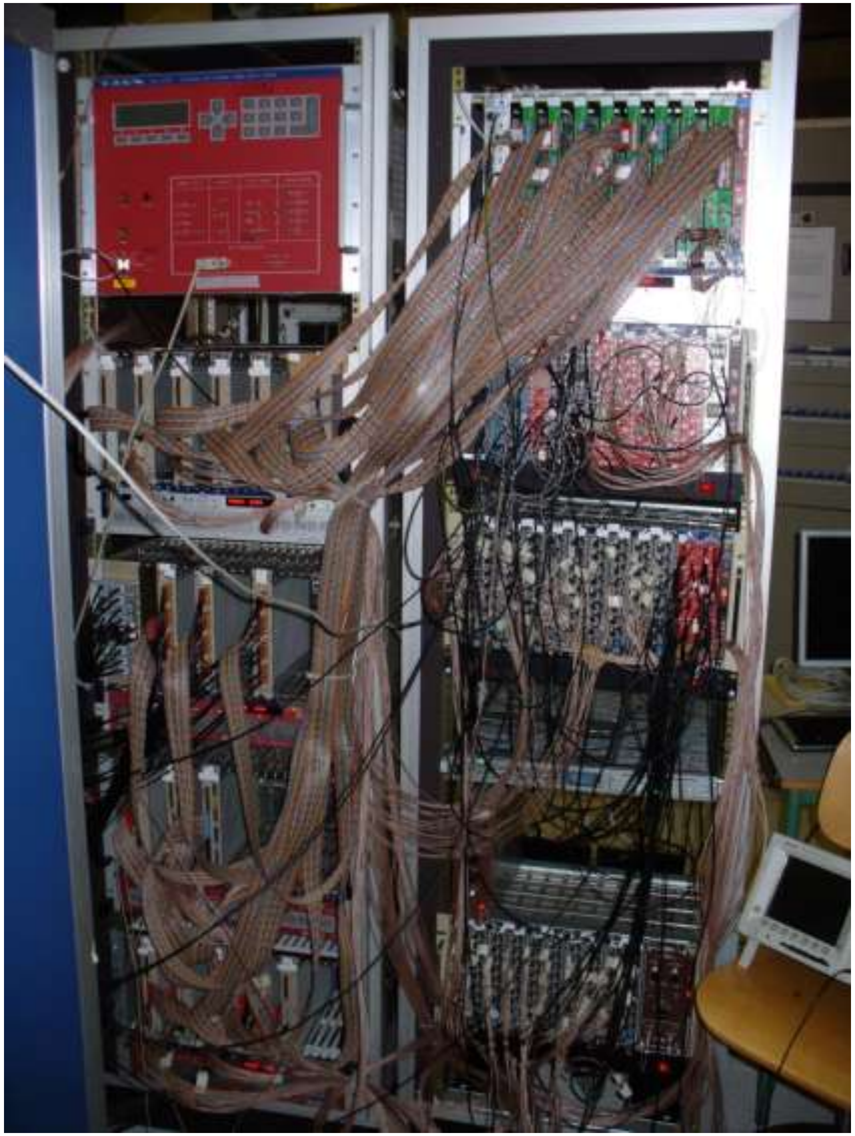


Detector telescopes: 50 x 50 mm^2

20 µm SSSD + 1000/500 µm PSD and DSSSD

Particle identification from p to cca ^{12}C





EuroGENESIS project

- involved in "Physics of compact objects: explosive nucleosynthesis and evolution" collaboration led by J. Jose UPC Barcelona
- funding 150,000 € in 3 years, PhD student, equipment, experiments
- use of our expertise from structure and reaction studies to study nuclear reactions important for stellar explosive phenomena: novae, SnIa , ccSn, X-ray bursts and super-bursts
- not direct low energy measurements of the reactions, focus on reactions which in astrophysically relevant energy range are likely to proceed through **resonances** which dramatically increase cross section of the reaction
- our main goal and objective is to obtain new results on the properties of these resonances and their full characterization
- full characterization of the resonances => obtained data will be important ingredients for calculations of improved reaction rates
- these indirect measurements complement direct measurements and provide useful input for setup of future direct experiments

Carbon – carbon burning

- Objective: search for $^{12}C+^{12}C$ resonances at ^{24}Mg excitations 15 - 20 MeV and full characterization of the resonances (excitation energy, width, spin, parity, partial decay widths)
- Two-fold reason: nuclear structure & astrophysical motivation

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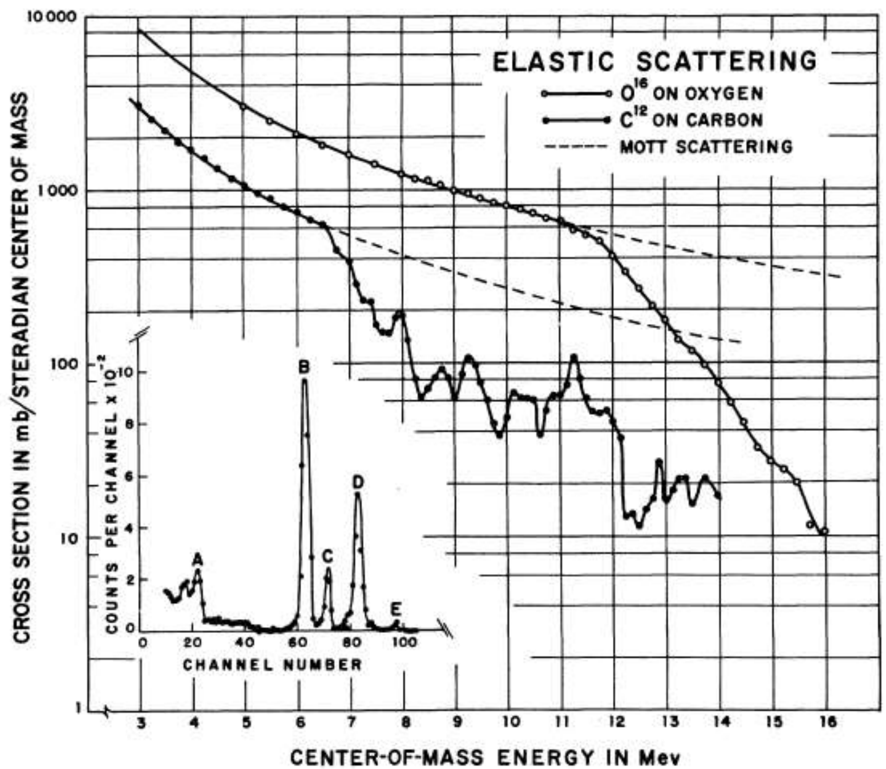
D. A. Bromley,
J. A. Kuehner,
E. Almquist, Phys.
Rev Lett 4 (1960) 385

Elastic scattering data

Resonant phenomena in heavy ion reaction

FIG. 1. Excitation curves for the elastic scattering of C^{12} by carbon and of O^{16} by oxygen. Self-supporting targets of carbon (~50μg/cm^2) and of SiO (~70μg/cm^2) and 5×5 mm Au-Si detectors, have been used in these measurements. The inset figure is a typical spectrum at θ_{lab}=45° obtained for 21.0-Mev carbon ions on carbon. The peak legend is as follows: the double peak at A arises from alpha particles and protons from the reaction which completely traverse the junction and thus provide a measure of its thickness. B is from C^{12} elastically scattered by carbon; C is for C^{12} elastically scattered by oxygen; D is from C^{12} elastically scattered by a residual phosphorous contaminant from the stripping compound used in preparing the target, and E is from C^{12} elastically scattered from traces of heavier target contaminants.



365

E. Almquist, D. A. Bromley, J. A. Kuehner, Phys Rev Lett 4 (1960) 515

Reaction data

Formation of quasi-molecular states in ^{24}Mg

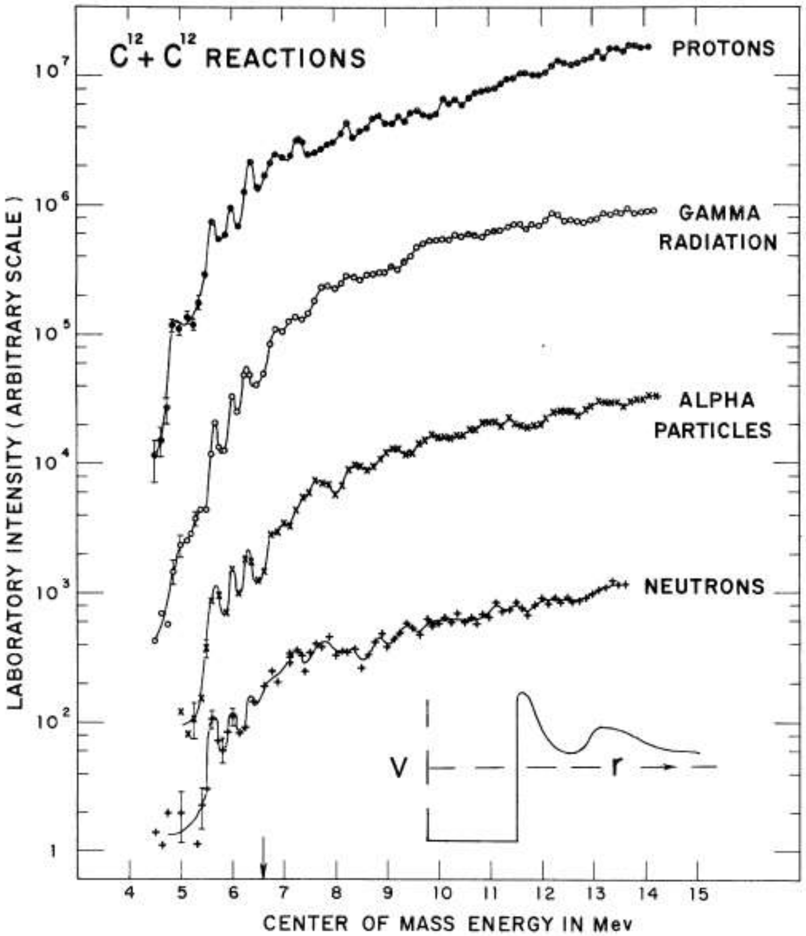


FIG. 1. Excitation curves for C^{12} on carbon reactions: protons at 27°, alpha particles at 42°, neutrons at 30°, and gamma radiation at 90°. The magnitudes of the corresponding differential cross sections (laboratory system) at 10 Mev (c.m. system) incident energy are: protons – 15 mb/sr, alpha particles – 34 mb/sr, and neutrons – 3 mb/sr. These cross sections refer to protons >6 Mev laboratory energy, alpha particles >7.5 Mev, and all neutrons. Detectors were, respectively: Si $p-n$ junctions (reference 2) covered by 0.007 inch of Al for protons, Au-Si surface barrier detectors (reference 2) covered by 0.001-inch Al for alpha particles, long counter of Hanson-McKibbon type for neutrons, and NaI crystal detectors biassed to detect gamma radiation >2.8 Mev energy. Target was a self-supporting ~40-μg/cm² C foil. Statistical errors are indicated where they are significantly larger than the points. The classical Coulomb barrier is indicated at 6.6 Mev. The inset shows the quasi-molecular potential envisaged.

E. Almquist, D. A. Bromley, J. A. Kuehner, Phys Rev Lett 4 (1960) 515

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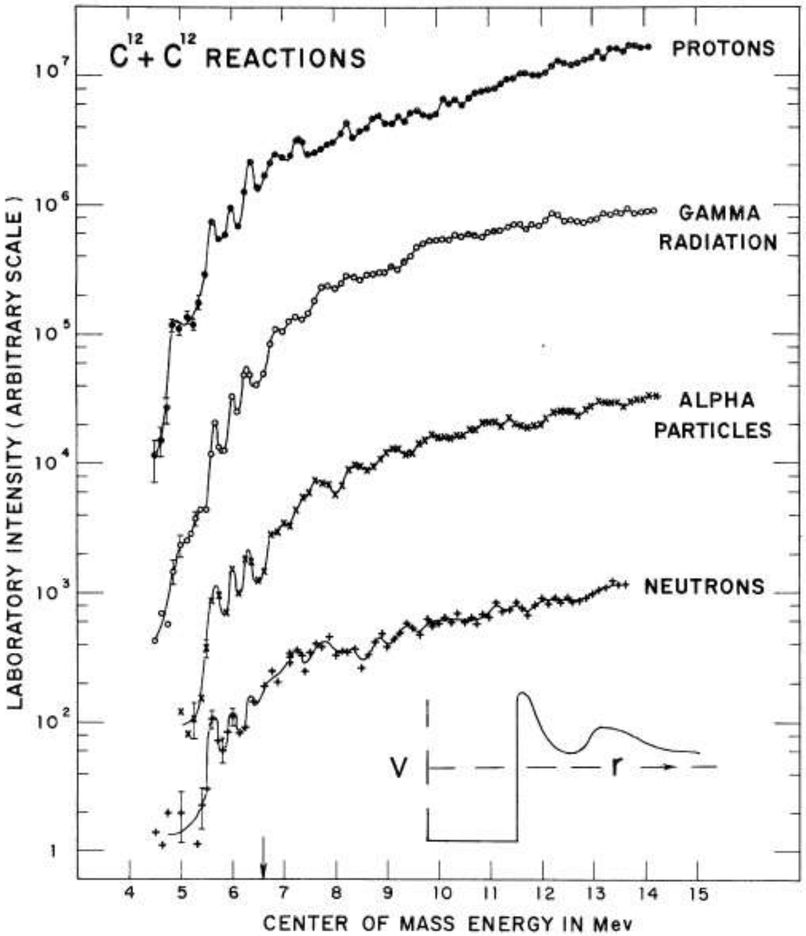

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50 years later:

- number of resonances decaying into various channels
- kind of unique nuclear system, very complex structure
- governed by cluster structure of ^{12}C – oblate deformation in gs
- **not fully understand yet**

B. R. Fulton et al, Phys Lett B 267 (1991) 325

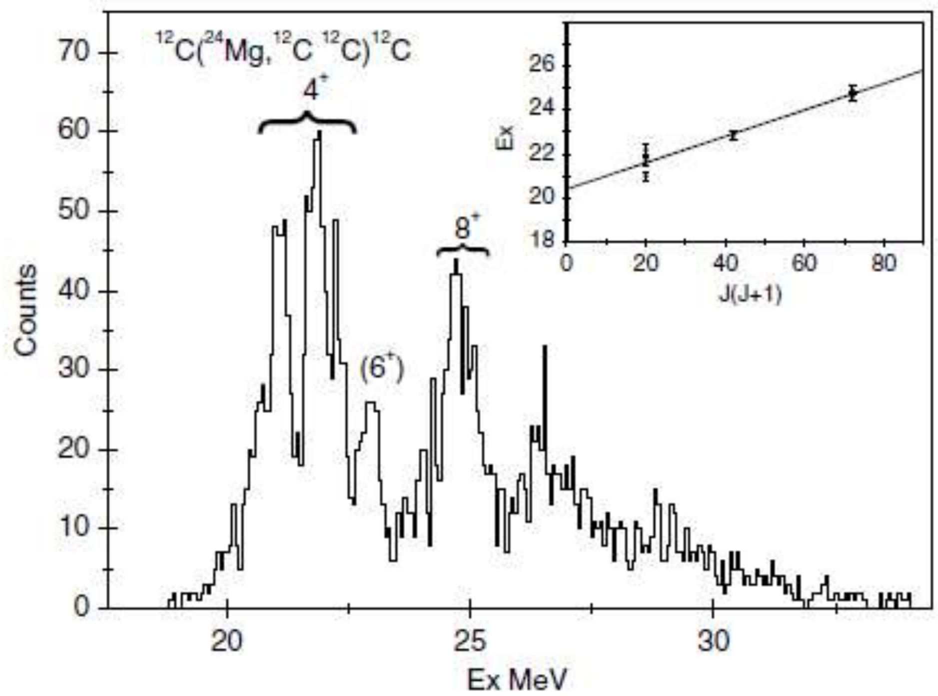
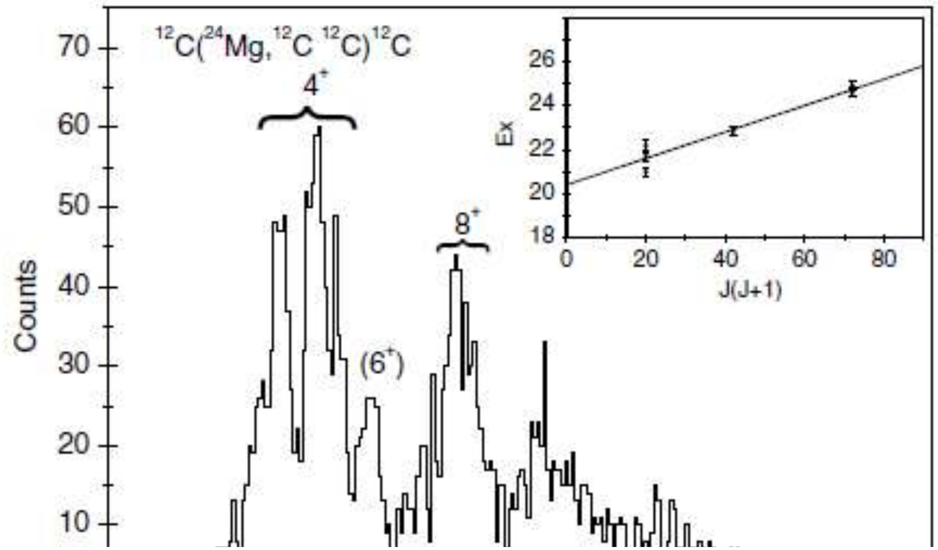


Figure 40. The excitation energy spectrum of ^{24}Mg corresponding to the breakup into two ^{12}C nuclei, from the $^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C$ reaction. The energy-spin systematics of the break up states are shown in the inset, from [143].

B. R. Fulton et al, Phys Lett B 267 (1991) 325

M. Freer et al, Phys Rev C 57 (1998) 1277

C. Metelko et al, Phys Rev C 68 (2003) 054321



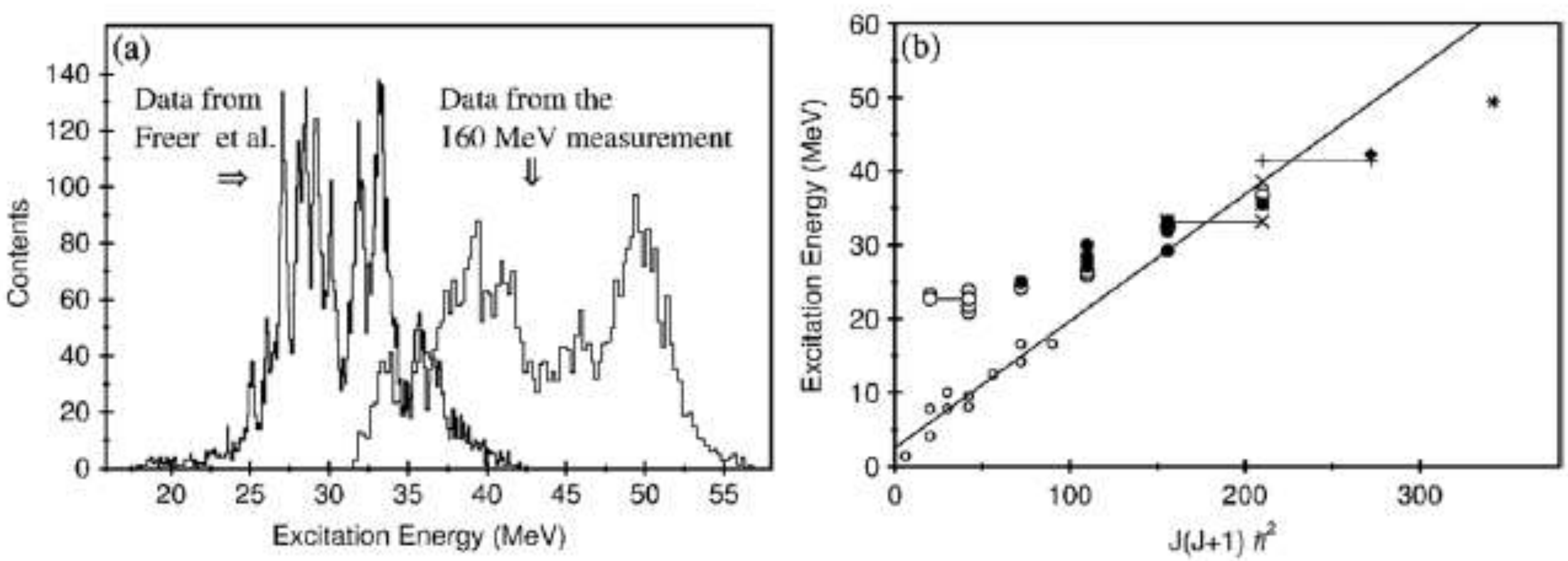


Figure 42. (*a*) Resonances observed in the $^{12}C(^{16}O,^{24}Mg^{*})$ breakup reaction [147, 148]. (*b*) The energy-spin systematics of the breakup resonances, from [148]. The smaller symbols and the solid line indicates the trend of the yrast states in ^{24}Mg.

M. Freer et al, Phys Rev C 57 (1998) 1277

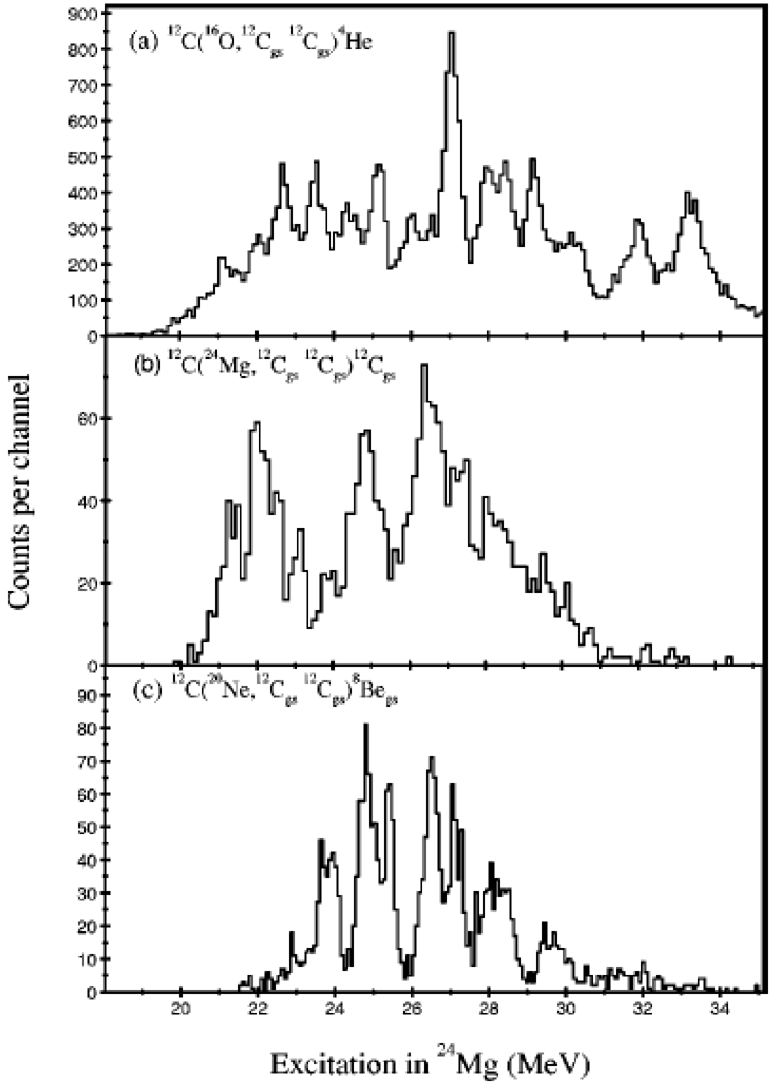


FIG. 10. A comparison of the ^{24}Mg excited states observed in the $^{12}C+^{12}C$ decay channel, populated in the reactions (a) $^{12}C(^{16}O,^{24}Mg^{*})$, (b) $^{12}C(^{24}Mg,^{24}Mg^{*})$ [8], and (c) $^{12}C(^{20}Ne,^{24}Mg^{*})$ [10,8].

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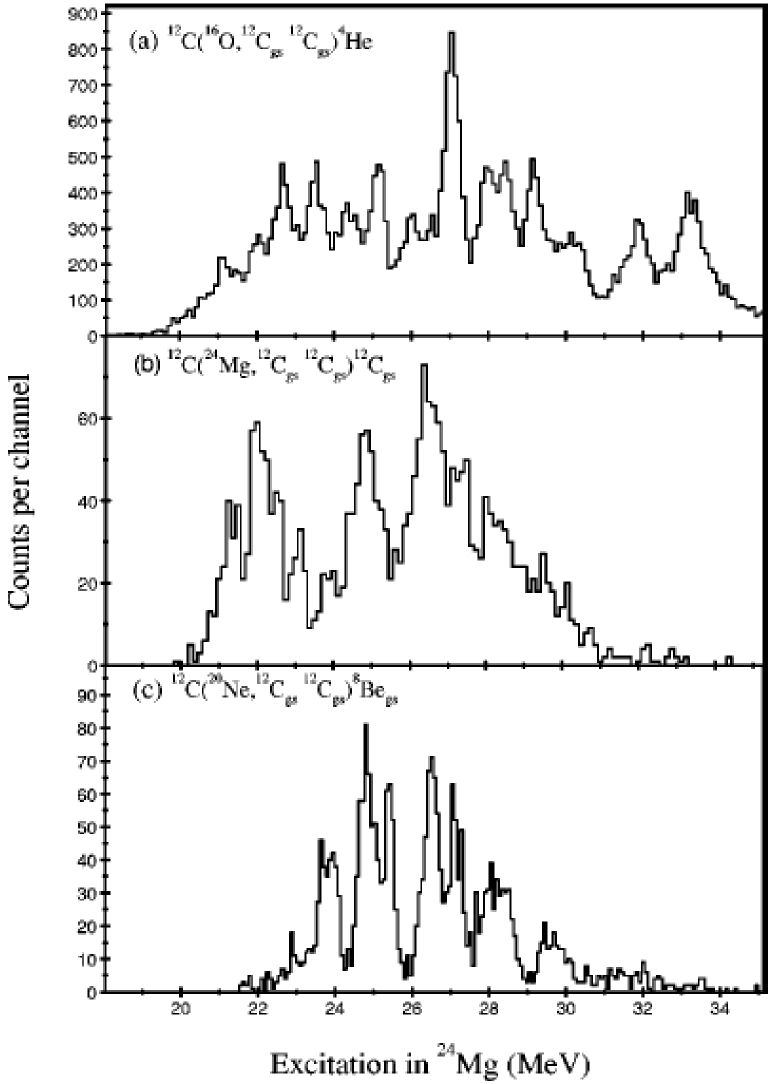

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But main focus of these studies has been on higher excitations in ^{24}Mg

No data below 20 MeV !

- Low energy data for $^{12}C+^{12}C$ fusion reaction crucial for many astrophysical phenomena: quiescent burning of massive starts, super-AGB stars, super-bursts and supernovae type Ia
- The most relevant quantity: total reaction fusion rate

$12C + 12C \rightarrow 24Mg +$?

$1^{2C} + 12C \rightarrow 20Ne + \alpha$

$1^{2C} + 12C \rightarrow 23Na + p$

$12C + 12C \rightarrow 23Mg + n$

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1^{2C} + 12C → 23Na + p

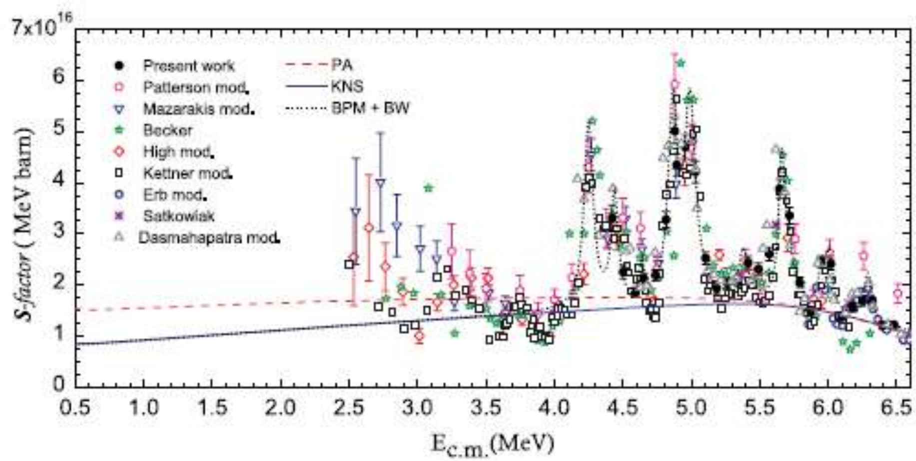
12C + 12C → 23Mg + n

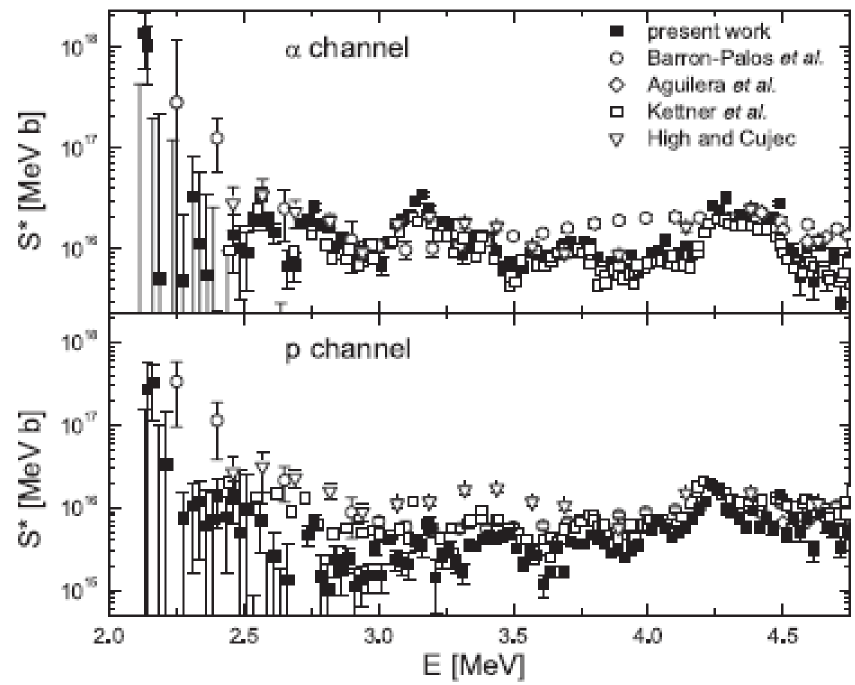
Existing data show large discrepancies

Low energy resonance ?

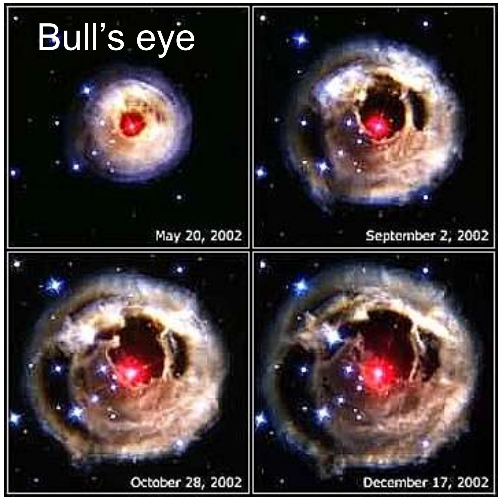
E. F. Aguilera et al, Phys. Rev. C 73 (2006) 064601

T. Spillane et al, Phys. Rev. Lett. 98 (2007) 122501





Stellar outbursts



$^{12}C+^{12}C$ fusion is differentiating between the evolutionary paths leading to either white dwarf or heavy elements burning stages

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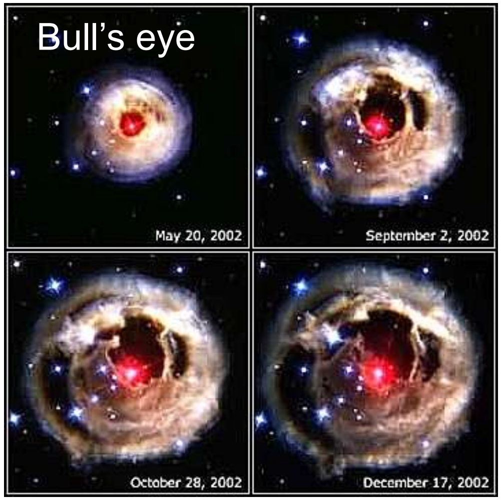


$^{12}C+^{12}C$ fusion is differentiating between the evolutionary paths leading to either white dwarf or heavy elements burning stages

Explosive phenomena in binary systems

SNIa: initiates thermonuclear runaway on white dwarf temperature range is

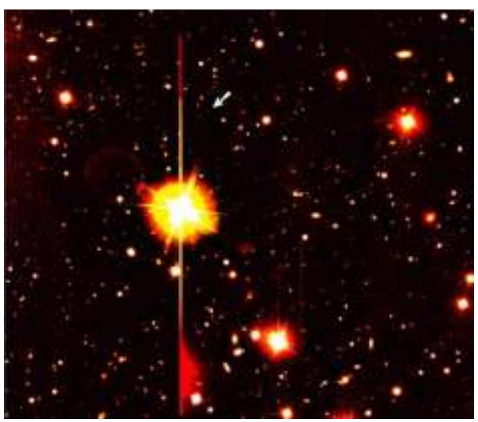
$0.5 - 1.2 \times 10^9$ K

E_{cm}=1.5-3.3 MeV

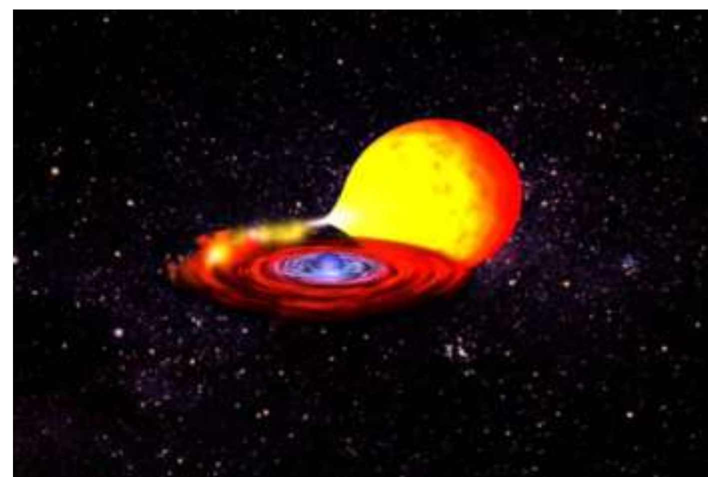
Super-bursts: trigger of ^{12}C ignition

up to 2.5×10^9 K - 5.7 MeV

Gamma Ray Bursts



most powerful events since the Big Bang (energy released in few seconds larger than Sun's output over its entire lifetime)



$^{12}C+^{16}O$ measurement at LNS Catania Apr 2010

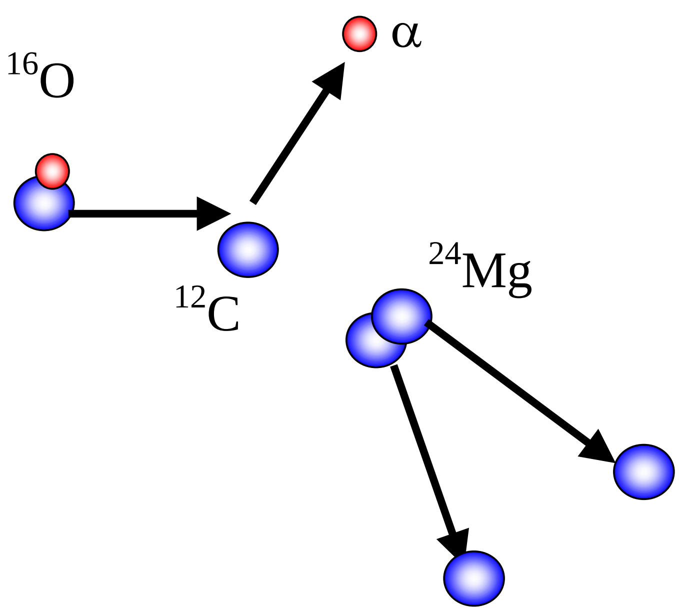
Coincident detection of 2 reaction products

$^{12}C + ^{16}O \rightarrow ^{4}He + ^{12}C + ^{12}C$ Q=-7.16 MeV $E_{thr}(^{24}Mg)$=13.93 MeV

$\rightarrow$ 4He + 16O + 8Be Q=$_{-7.}$3^{7} MeV Ethr(24Mg)= 14.14 MeV

$\rightarrow$ 4He + 20Ne + 4He Q=-$_{2.5}$4 ^{M}eV Ethr(24Mg)= 9.31 MeV

$\rightarrow$ 4He + 23Na + 1H Q=$_{-4.}$9^{2} MeV Ethr(24Mg)= 11.69 MeV



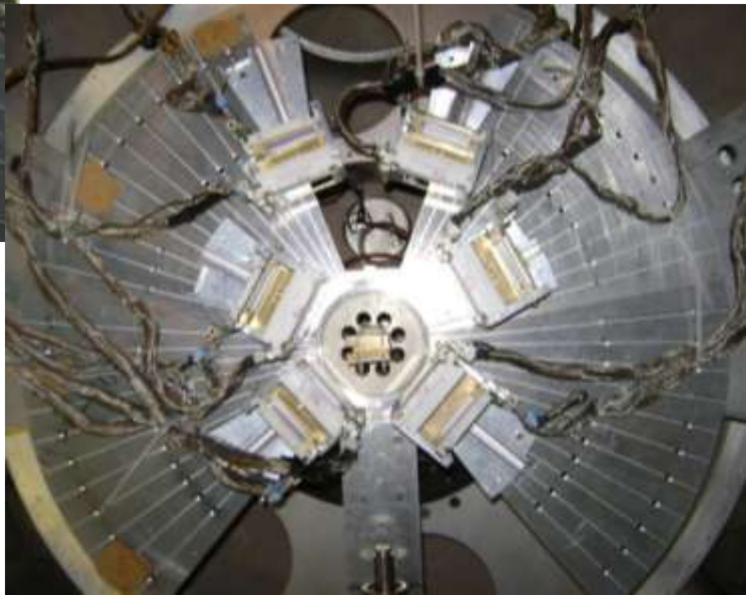
Excitation energy range: 1 – 6 MeV above the $^{12}C + ^{12}C$ threshold, 15 – 20 MeV in ^{24}Mg excitation

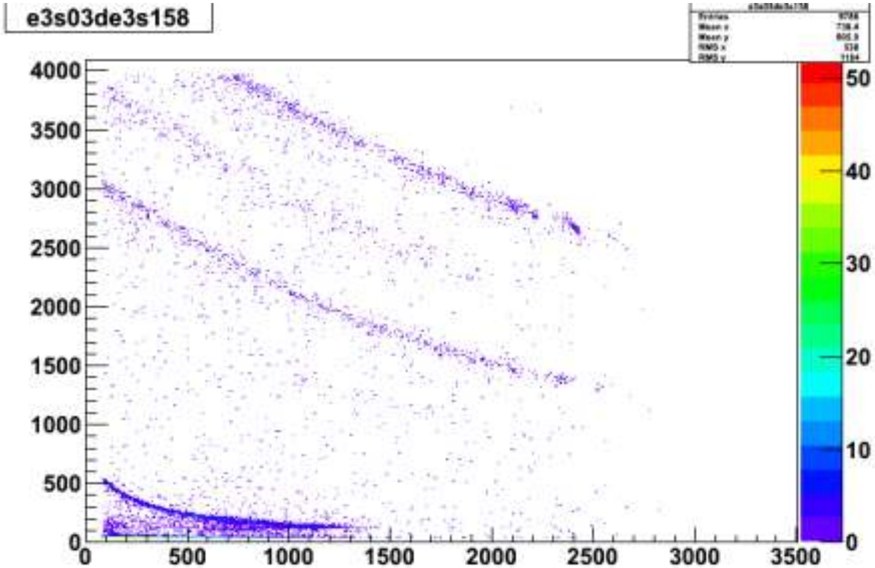
Resonance parameters:
excitation energy, width,
spin, parity and partial decay widths
of the resonances

Main goal: identify low spin states with significant $^{12}C+^{12}C$ partial width

^{16}O beam energy: 90 MeV, target: 60 μm/cm^2 carbon target

RBI, Uni of Zagreb
INFN-LNS Catania,
Uni of Birmingham,
Uni of Huelva

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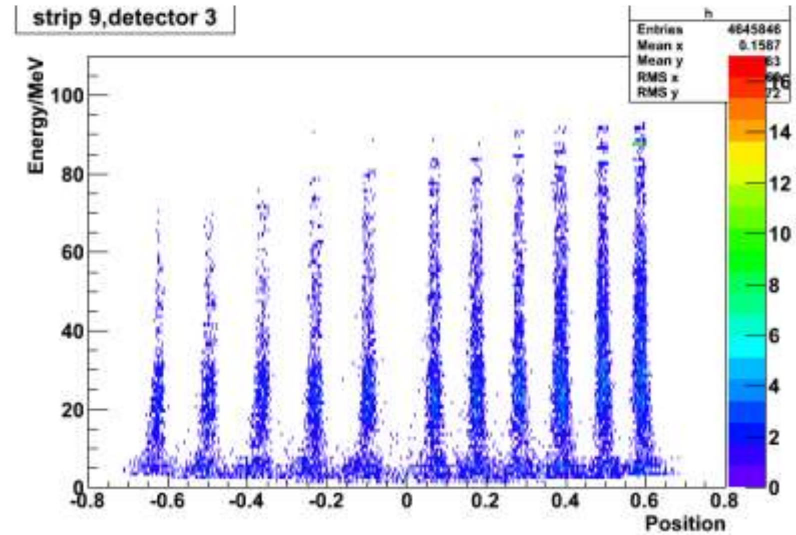
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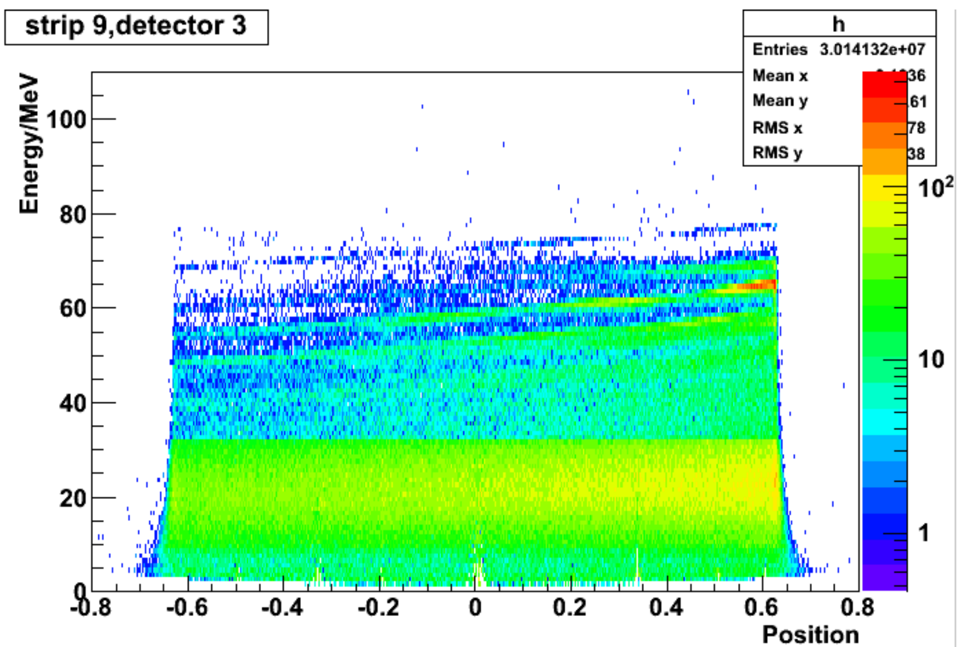
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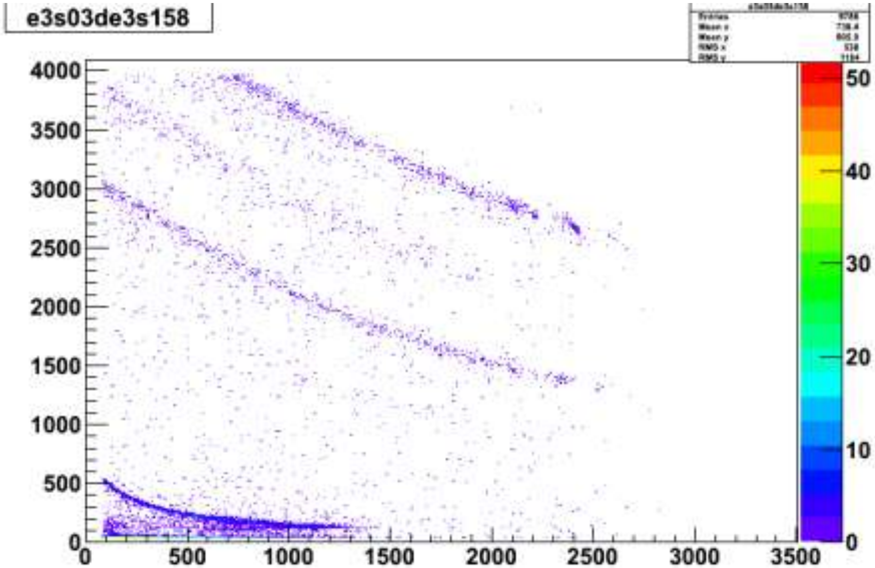
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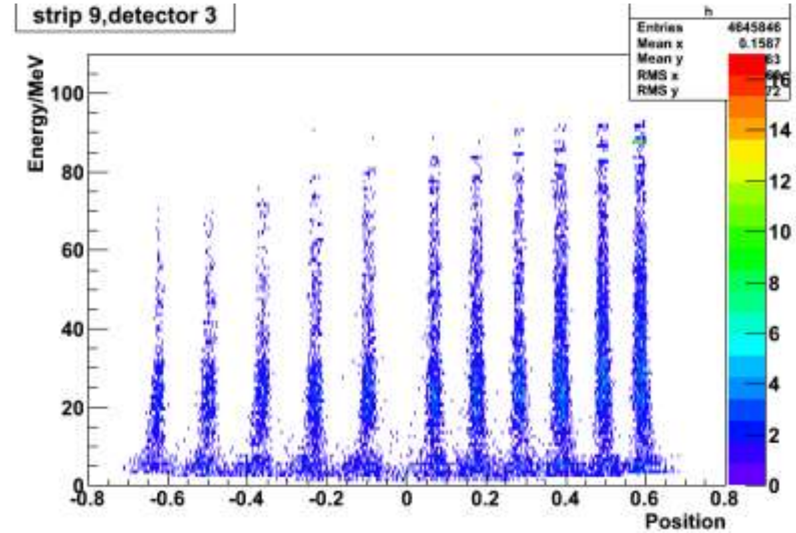
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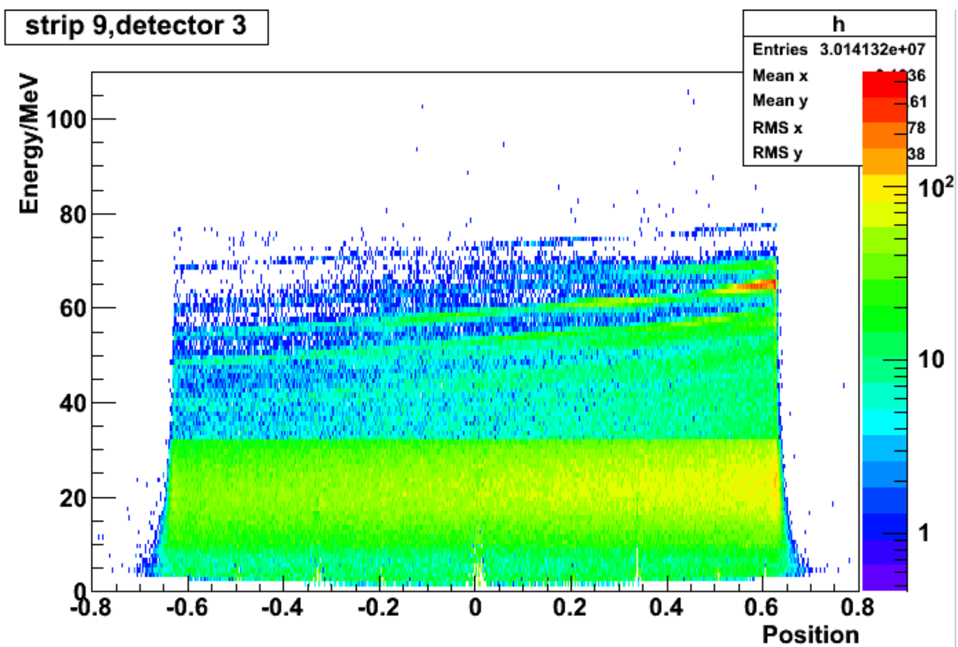
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RMS x
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Energy/MeV
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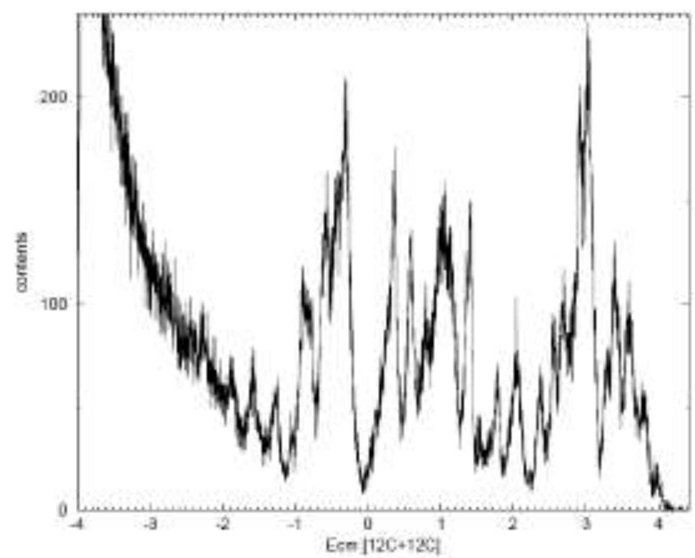
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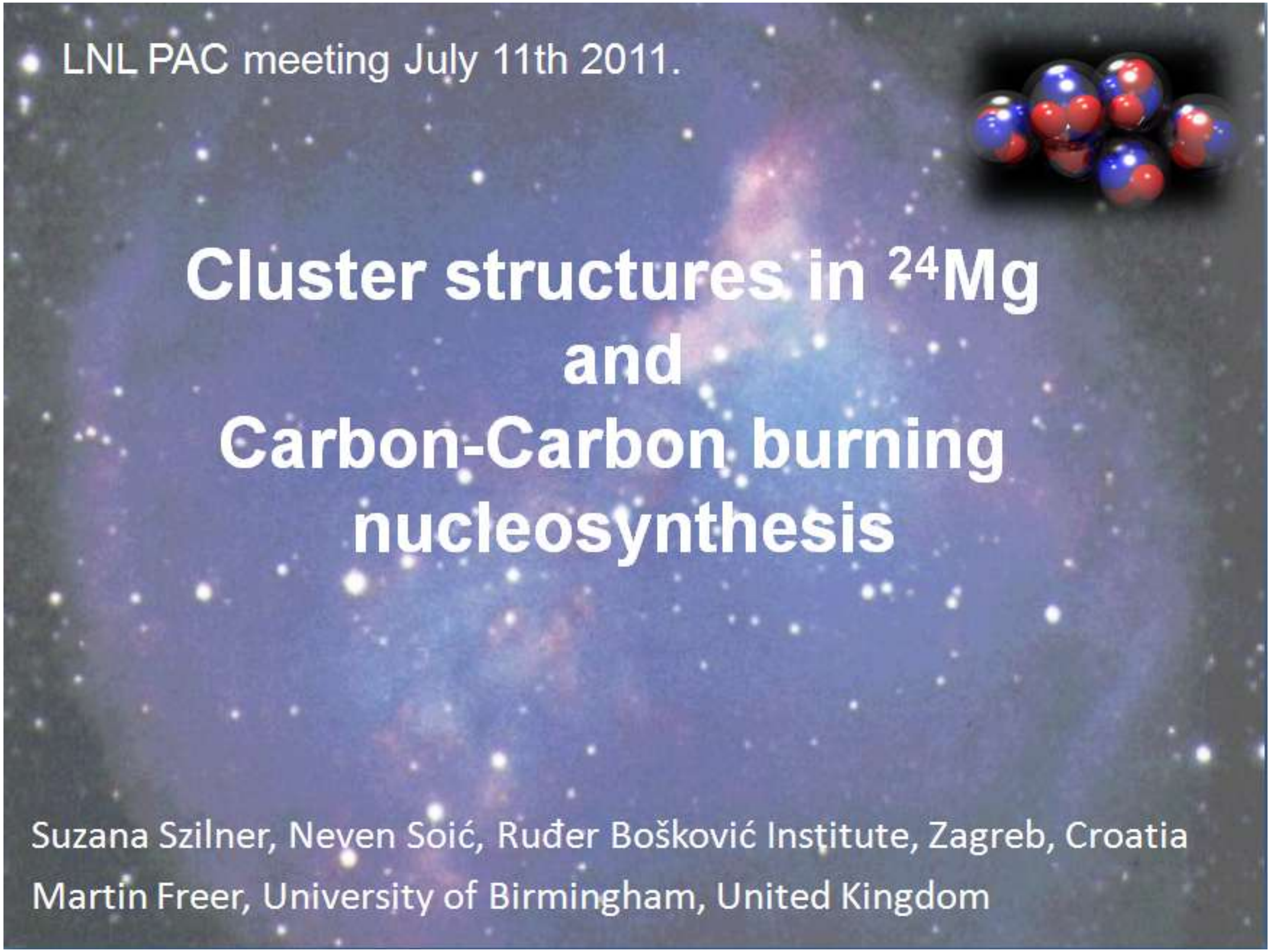
3
4

Direct measurements of C–C burning and more



Experimental technique

- heavy ion beam: ^{20}Ne / ^{23}Na for ^{24}Mg studies, ^{22}Ne for ^{26}Mg
- light gas target: ^{4}He / ^{1}H – all chamber volume filled up at low pressure (astrophysical), ^{4}He high pressure (structure studies)

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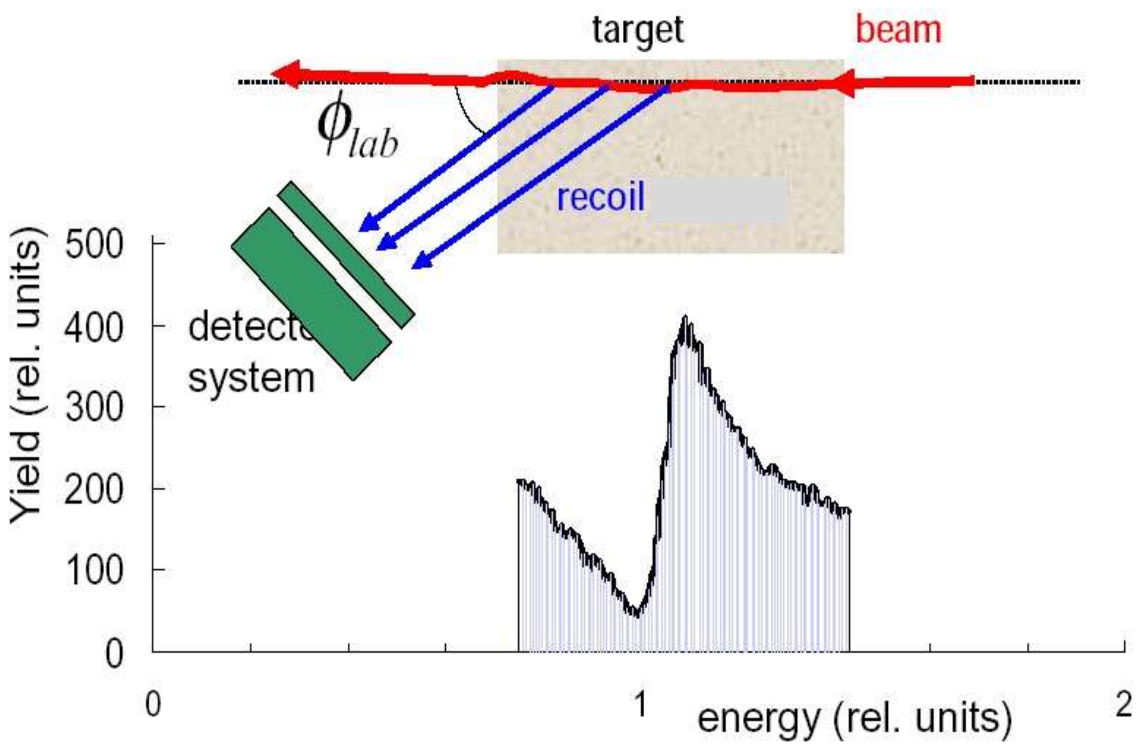
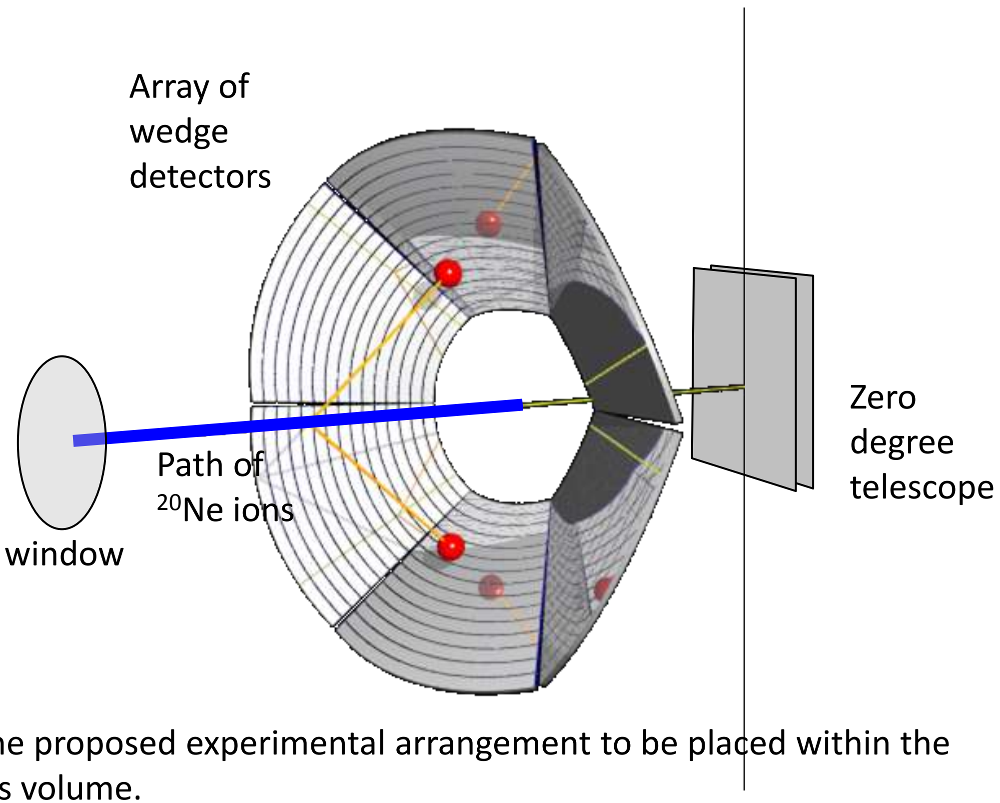
- resonant scattering and resonant reactions



beam slows down through gas, at resonance energy enhanced scattering and production of ^{12}C+^{12}C

- coincidence detection of all reaction products
- kinematically complete measurements



The proposed experimental arrangement to be placed within the gas volume.

- large silicon array assembled of DSSD (500, 1000 μm), SSSD (20 μm) and wedge YY1 type Micron Semiconductor

- particle identification: kinematics, but if required TOF & ΔE-E telescopes
-measurements of angular distributions

Full resonance characterization

Astrophysical measurements

Measurement of $^{20}Ne(\alpha,^{12}C)^{12}C$ reaction

- ^{4}He gas target – scattering chamber filled up with gas at low pressure
- ^{20}Ne beam of 60 – 100 MeV – PIAVE + ALPI
- Q = - 4.62 MeV
- reaction products identical => particle identification using reaction kinematics

Measurement of $^{23}Na(p,^{12}C)^{12}C$ reaction

- ^{23}Na beam energy 70 – 130 MeV – TANDEM + ALPI
- target: low pressure H_2 gas due to safety restrictions
- Q = - 2.24 MeV

Expected results

In summary, expected results of the measurements will provide new information about following issues :

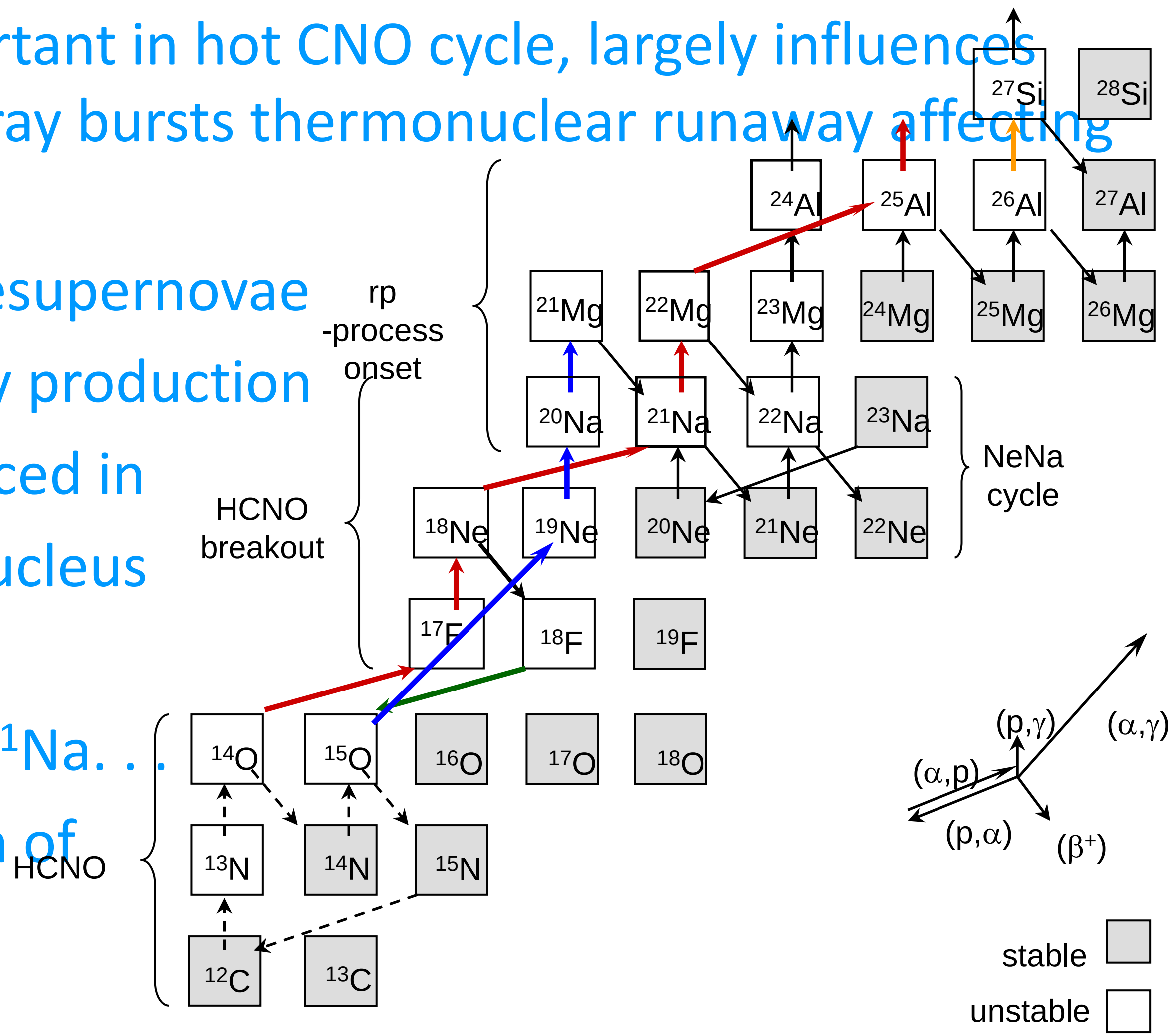
1) How many resonances exist at ^{24}Mg excitations 15.5 – 20 MeV ?
2) Is there any $^{12}C+^{12}C$ resonance at low excitations 15.5 – 16.5 MeV and what are resonance parameters ?
3) Is there any low spin resonance which may influence carbon-carbon burning and how much it affects reaction rate ?
4) Are there structures at high excitations made of α-particles correlated into ^{8}Be or ^{12}C(7.65 MeV) ?
5) Do observed resonances help in explaining ^{24}Mg structure ?
6) How addition of 2 neutrons changes cluster structure in ^{26}Mg ?

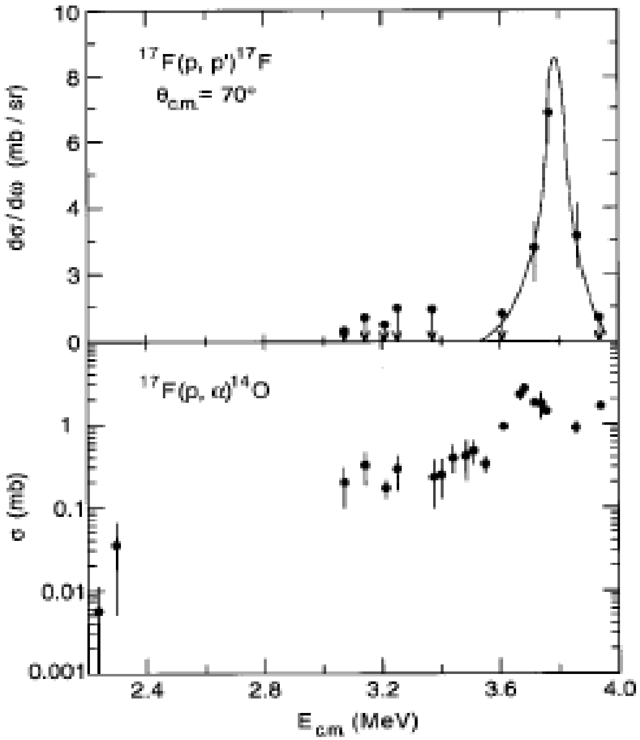
Resonances in ^{18}Ne

- important for reaction rates of the $^{14}O(\alpha,p)^{17}F$ and $^{17}F(p,\gamma)^{18}Ne$ reactions at relevant energies in stellar explosions
- the 1st reactions is important in hot CNO cycle, largely influences energy production in X-ray bursts thermonuclear runaway affecting later nucleosynthesis
- very massive stars in presupernovae phase – increase energy production
- ^{14}O ($T_{1/2}$=70,61 s) produced in hCNO is waiting point nucleus
- αp-process

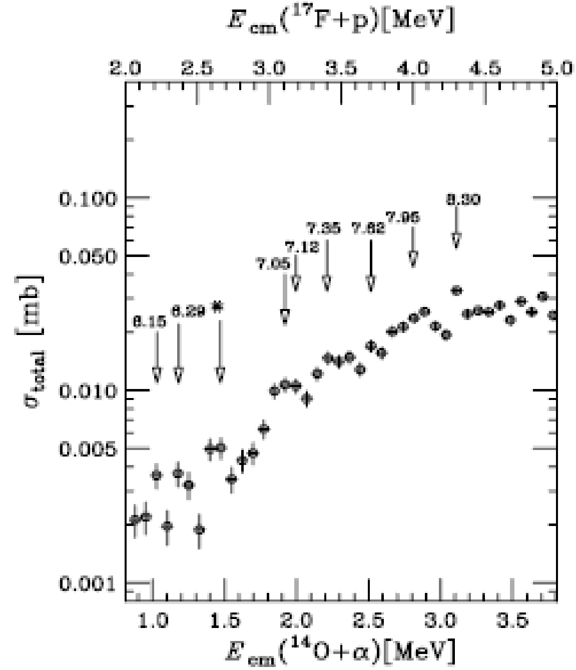
$^{14}O(\alpha,p)^{17}F(p,\gamma)^{18}Ne(\alpha,p)^{21}Na$. . .

- rp-process – production of nuclei up to Cadmium





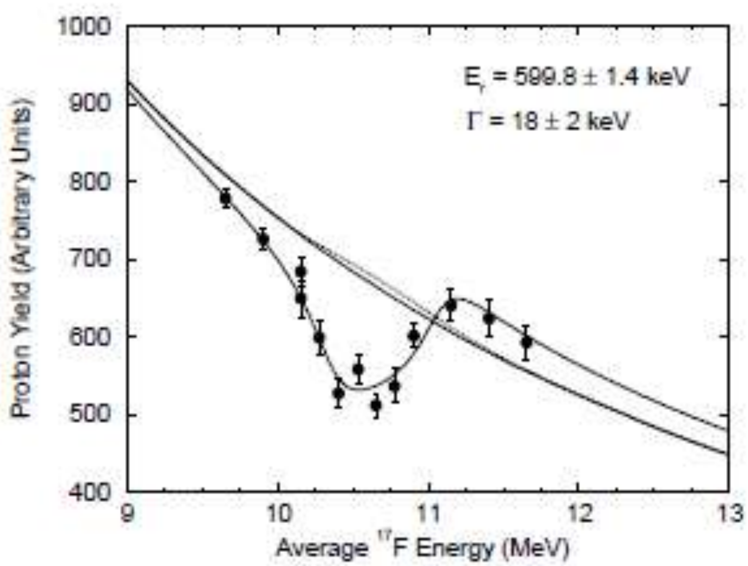
Inverse reaction measurements
B. Harss et al, Phys. Rev. C 65 (2002) 035803



Direct measurements
M. Notani et al, Nucl. Phys. A 746 (2004) 113c

- the reaction rate is dominated by the single 1^- state of ^{18}Ne at 6.15 MeV
- states at excitations above 7 MeV $E_x(J^\pi)$=7.05 (4^+), 7.37 (2^+), 7.60 (1^-), 7.71 MeV (2^-) also contribute but their effect on the reaction rate is quite uncertain

- the 2nd reaction is of importance for novae nucleosynthesis, escape from HCNO, preburst energy generation in x-ray bursts
- novae: production and destruction of ^{18}F ($T_{1/2}$=110 min)
- **x-bursts: the $^{16}O(p,\gamma)^{17}F(p,\gamma)^{18}Ne(e^+\nu_e)^{18}F(p,\alpha)^{15}O$ reaction sequence produces peak energy during the ignition phase**

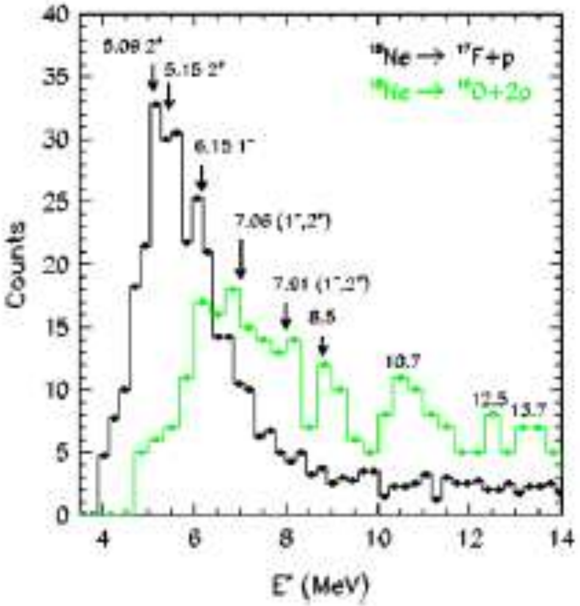


D. W. Bardayan et al, Phys. Rev. Lett. 83 (1999) 45

the 3^+ state (l=0 resonance) at 4.524 MeV dominates the resonant capture cross section

- study of ^{18}Ne resonances in relevant excitation energy range (4.0-6.5 MeV) by studying decays of $^{18}Ne^*$ into $^{14}O+\alpha$, $^{17}F+p$ and $^{17}F^*$(495 keV)+p’

Nuclear structure of proton-rich nuclei



G. Raciti et al, Phys. Rev. Lett. 100 (2008) 192503

^{2}He diproton decay of the 6.15 MeV 1^{-} state

other 2p decaying states at higher excitations

democratic decay (uncorrelated emission of 2 p) or 2 sequential emissions of proton

Changbo Fu et al, Phys. Rev. C 76 (2007) 021603

Changbo Fu et al, Phys. Rev. C 77 (2008) 064314

^{14}O+α resonant scattering - α-decaying states 8 – 17 MeV, cluster structure

Exotic cluster structures: ^{6}Be and ^{8}Be decaying states

- measurement of the breakup of radioactive ^{18}Ne beam on ^{12}C target into ^{14}O+α.^{17}F+p, ^{16}O+2p, ^{17}F*(495 keV)+p, ^{12}C+^{6}Be, ^{10}C+^{8}Be
- search for resonances at excitation energies between 4.5 to 25 MeV

Proposal submitted to GANIL PAC – Nov 2011.

Structure of ^{18}Ne and its astrophysical implications

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Other possible reactions for study of $^{18}Ne^*$ into $^{14}O+\alpha$ and $^{17}F+p$
Stable beam experiments, available some inclusive experimental data
Proposed coincident measurements:

1) $^{16}O(^{3}He,n)^{18}Ne^*$
2) $^{14}N(^{10}B,^{6}He)^{18}Ne^*$
3) $^{20}Ne(p,t)^{18}Ne^*$

Neutron rich light nuclei - search for three-centre structures in ^{14}C and ^{16}C

^{4}He DECAY OF EXCITED STATES IN ^{14}C

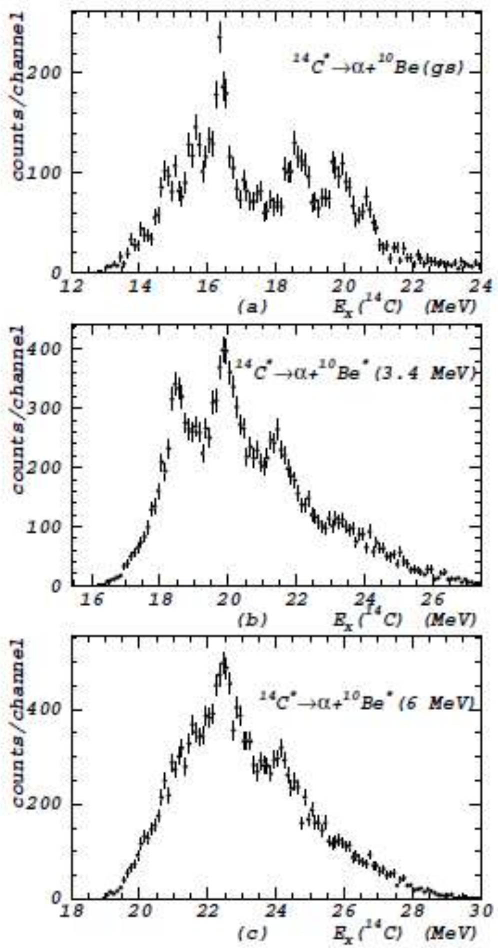


FIG. 2. ^{14}C excitation energy spectra for decays to (a) ^{10}Be ground state (b) ^{10}Be 3.4 MeV, 2^+ state, and (c) ^{10}Be excited states at ~6 MeV. Error bars represent statistical errors only.

N. Soić et al, Phys. Rev. C 68 (2003) 014321

PHYSICAL REVIEW C 68, 014321 (2003)

TABLE I. Excitation energies of ^{14}C states decaying into states in ^{10}Be. The uncertainties in these energies for decays to the ^{10}Be ground state and first excited state are 100 keV, and due to the ambiguity in the excitation energy of the 6 MeV peak, the uncertainty here is 300 keV. The previous measurements are from the tabulations of Ref. [15].

$^{10}Be_{gs}$	$^{10}Be(2^+)$	^{10}Be(6 MeV)	Previous
14.7(0.1)			14.667 (4^+)
15.5(0.1)			15.44 (3^-)
16.4(0.1)			16.43
18.5(0.1)	18.5(0.1)		18.5
	[19.1(0.1)]		
19.8(0.1)	19.8(0.1)		
20.6(0.1)			
	21.4(0.1)		
		22.4(0.3)	
	[23.2(0.1)]		
		24.0(0.3)	

Future: Search for ^{6}He decay of ^{14}C states

GANIL experiment E580S: Spectroscopy of neutron rich light nuclei: decays of ^{16}C and ^{5}H unbound states

RBI, Uni of Zagreb, Uni of Birmingham, INFN-LNS, Uni of Huelva, LPC Caen, GANIL, iThemba Labs

Measurement of the $^{6}He+^{18}O$ reaction: ^{16}C

objectives: characterization of the he-decaying excited states
identification of the members of the rotational bands.

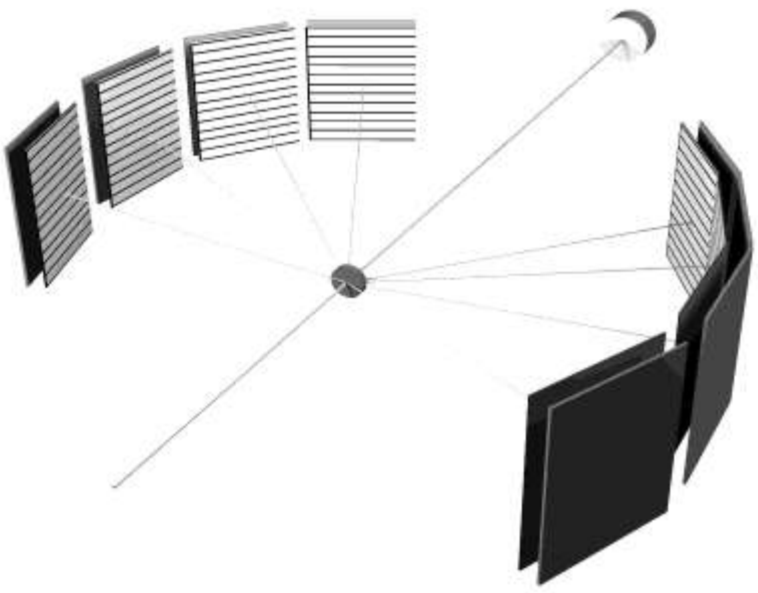
- rotational bands with triangular structure - oblate (band head 0^+ and 3^-) and linear chain structure – prolate (band head 0^+)
- the $^{18}O(^{6}He,^{8}Be)^{16}C^*$, $^{18}O(^{6}He,^{8}Be^{6}He)^{10}Be$ and $^{18}O(^{6}He,^{8}Be^{4}He)^{12}Be$ reactions
- 2 proton pick-up reaction $(^{6}He,^{8}Be)$

Measurement of the $^{6}He+^{7}Li$ reaction: ^{5}H

objectives: search for di-neutron decay of the resonances, identification of the ground state resonance

- measurements of the $^{7}Li(^{6}He,^{8}Be)^{5}H$ and $^{7}Li(^{6}He,^{8}Be^{3}H)2n$ reactions
- proton stripping from ^{6}He beam and 2 proton pick-up from ^{7}Li target

- SPIRAL beam 66 MeV, intensity 1-2x10^6 pps
- target: 600 μg/cm^2 $^7Li_2{}^{18}O$ on 50 μg/cm^2 C backing, isotopically enriched in ^{7}Li to 99% and ^{18}O to 90%
- 8 detector telescopes for charged reaction products in the reaction plane
- 20 μm thick SSSD, 1000 μm thick DSSSD and 2.5 cm thick CsI detector



Expected results

-^{16}C: characterization of states with large partial decay width for the he-decays, rotational bands, deformed molecular Structure: triangular and/or linear chain shape ⇒ three-centre clustering structure in neutron rich carbon nuclei

- ^{5}H: resonance decay into ^{3}H + di-neutron, existence of narrow $1/2^+$ ground state separated at lower excitation from $3/2^+$ and $5/2^+$ resonances

Summary and Conclusion

- Main focus on carbon – carbon burning
- Proposal for experiment on ^{18}Ne resonances submitted to GANIL – PAC in Nov 2011.
- Hoyle state and 3α structure
- Neutron-rich light nuclei program - carbon
- We might survive

Collaborators

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