Heavy-ion direct measurements

What nuclear structure and reactions can bring to astrophysics ?

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Outline

I. C burning, why is it important, what do we know ?

II. What our studies of reactions may bring

III. What our knoweledge of structure may bring

IV. Approaches to tackle the $^{12}C+^{12}C$ fusion reaction

V. Conclusions

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C burning, why is it important, what do we know ?

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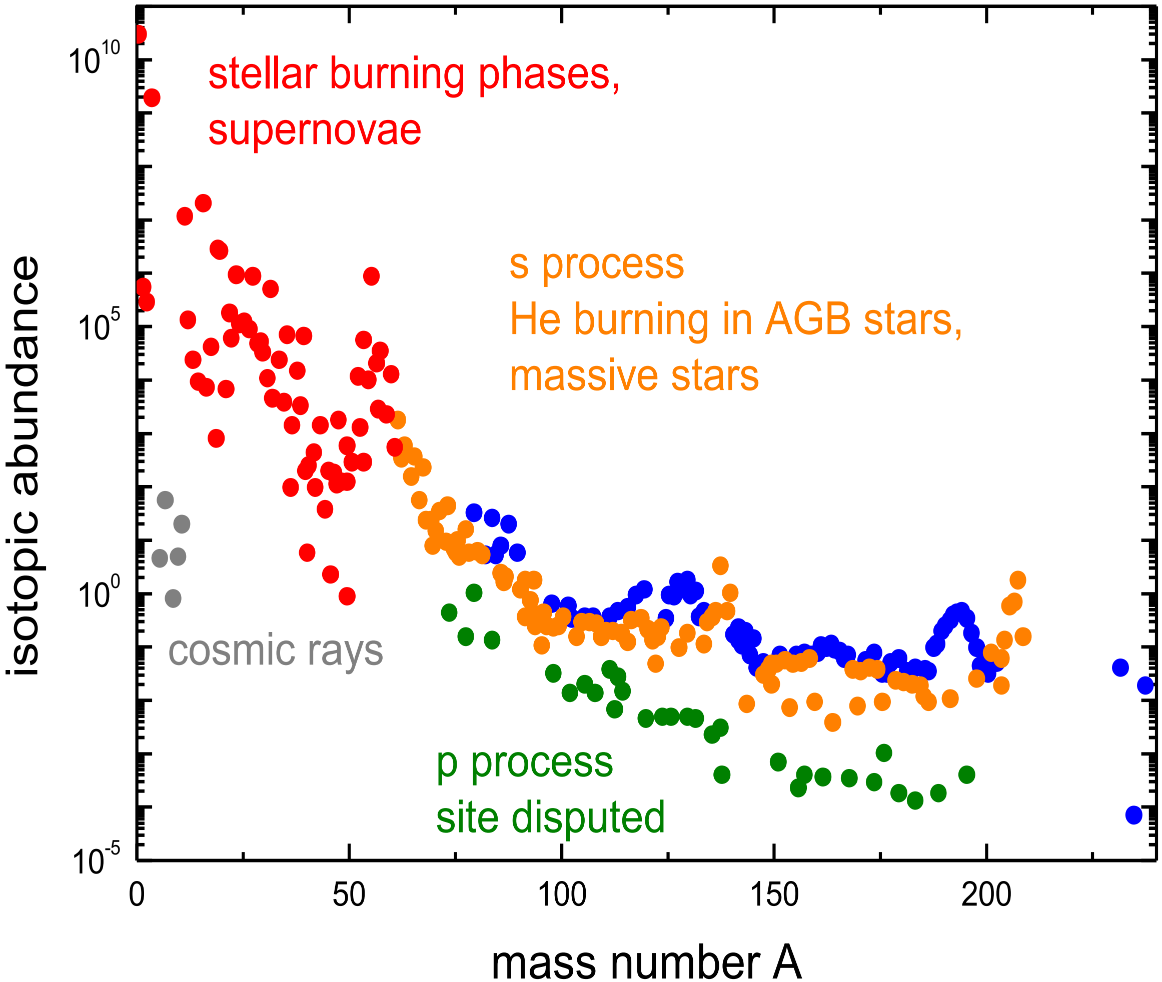
Isotopic abundances



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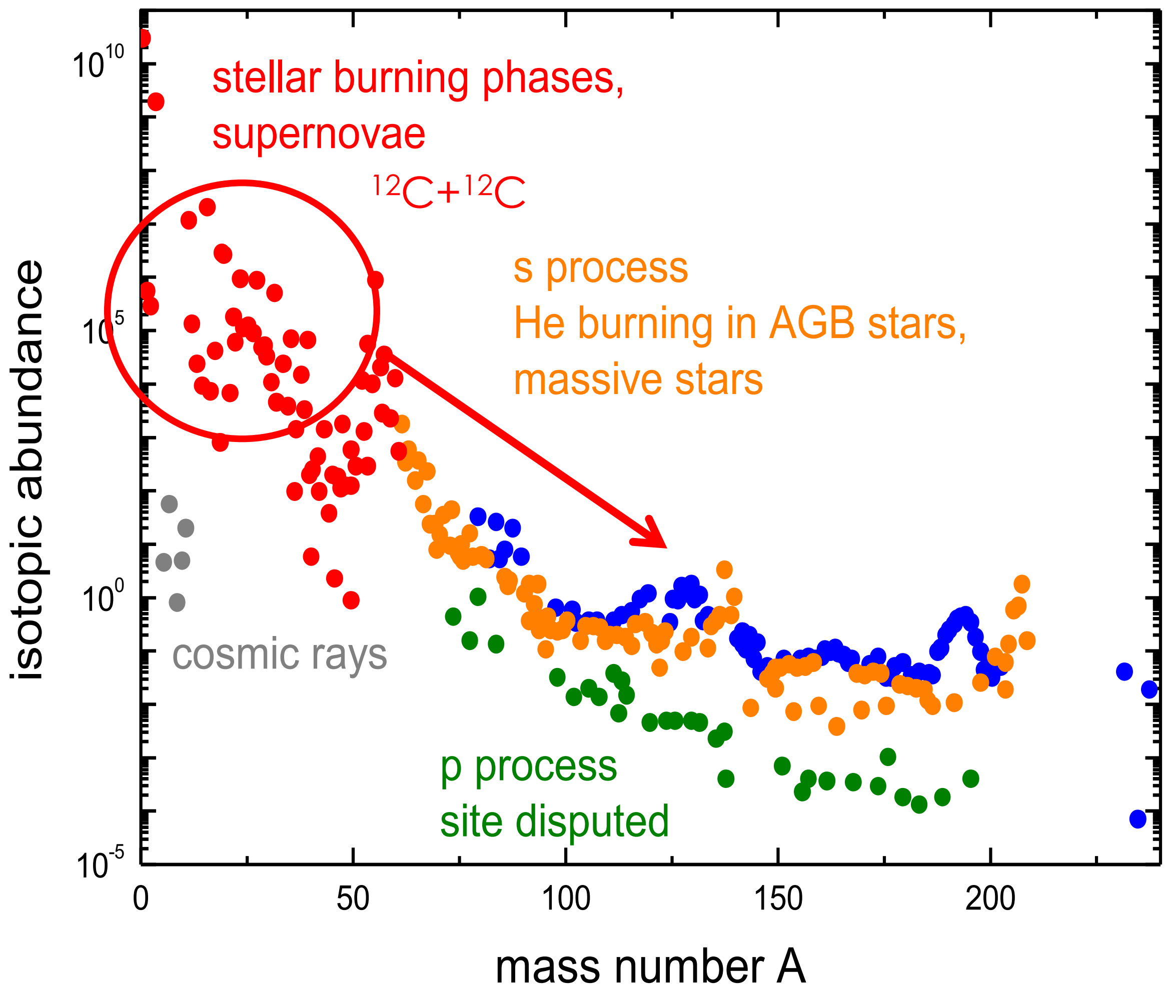
Isotopic abundances



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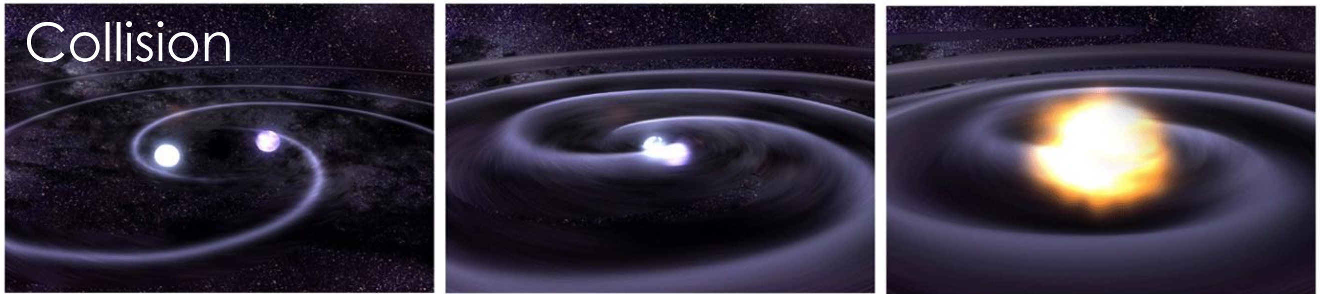
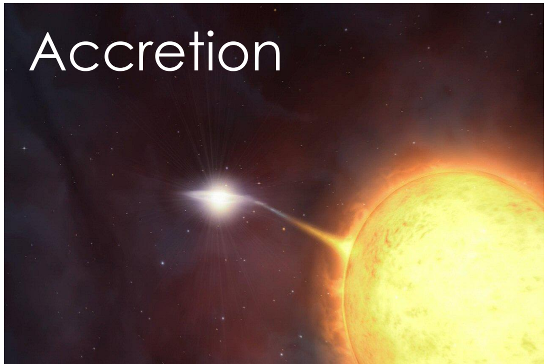
Carbon burning: a crucial phase in the stellar nucleosynthesis

- $M < 8\text{-}9\ M_\odot$ -> these stars are expected to shed their envelopes during helium burning and become white dwarfs, which may generate Type Ia supernovae

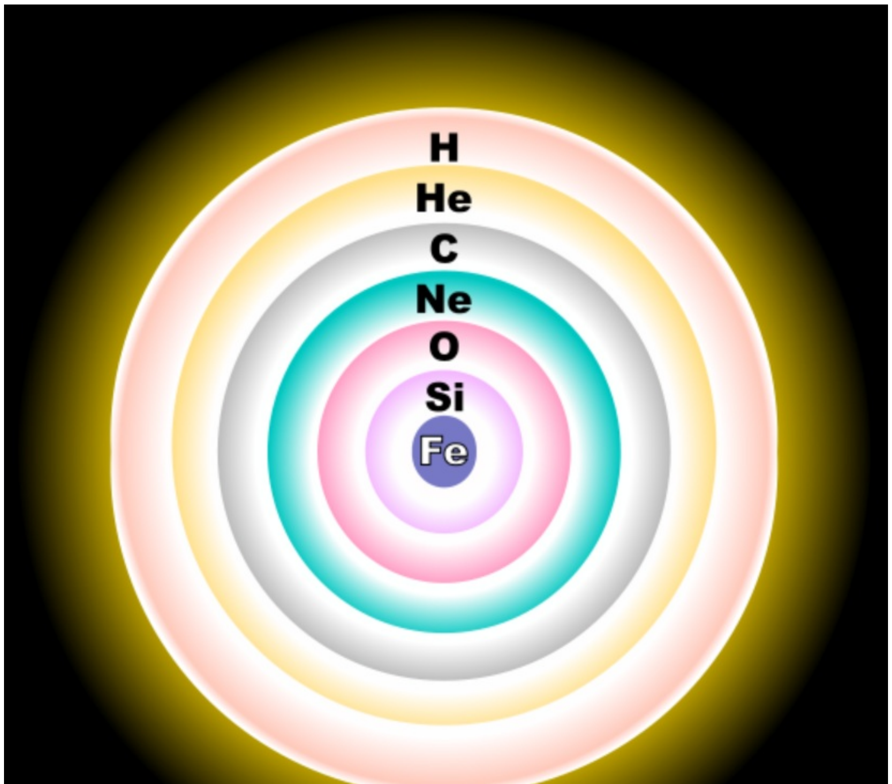
- $M = 9\text{-}11\ M_\odot$ -> burning could occur under a degenerate condition, carbon flash

- $M > 11\ M_\odot$ -> burning in a non-degenerate contracting core ($T > 10^8$ K, $\rho > 3.10^6$ g.cm^{-3})





Carbon burning: a crucial phase in the stellar nucleosynthesis



Different shells of a massive star shortly before core collapse

- key reactions at each stage of stellar burning

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)$…

- In a star of 8-11 Solar masses, a carbon flash lasts just milliseconds.
- In a star of 25 Solar masses carbon burning lasts about 600 years.

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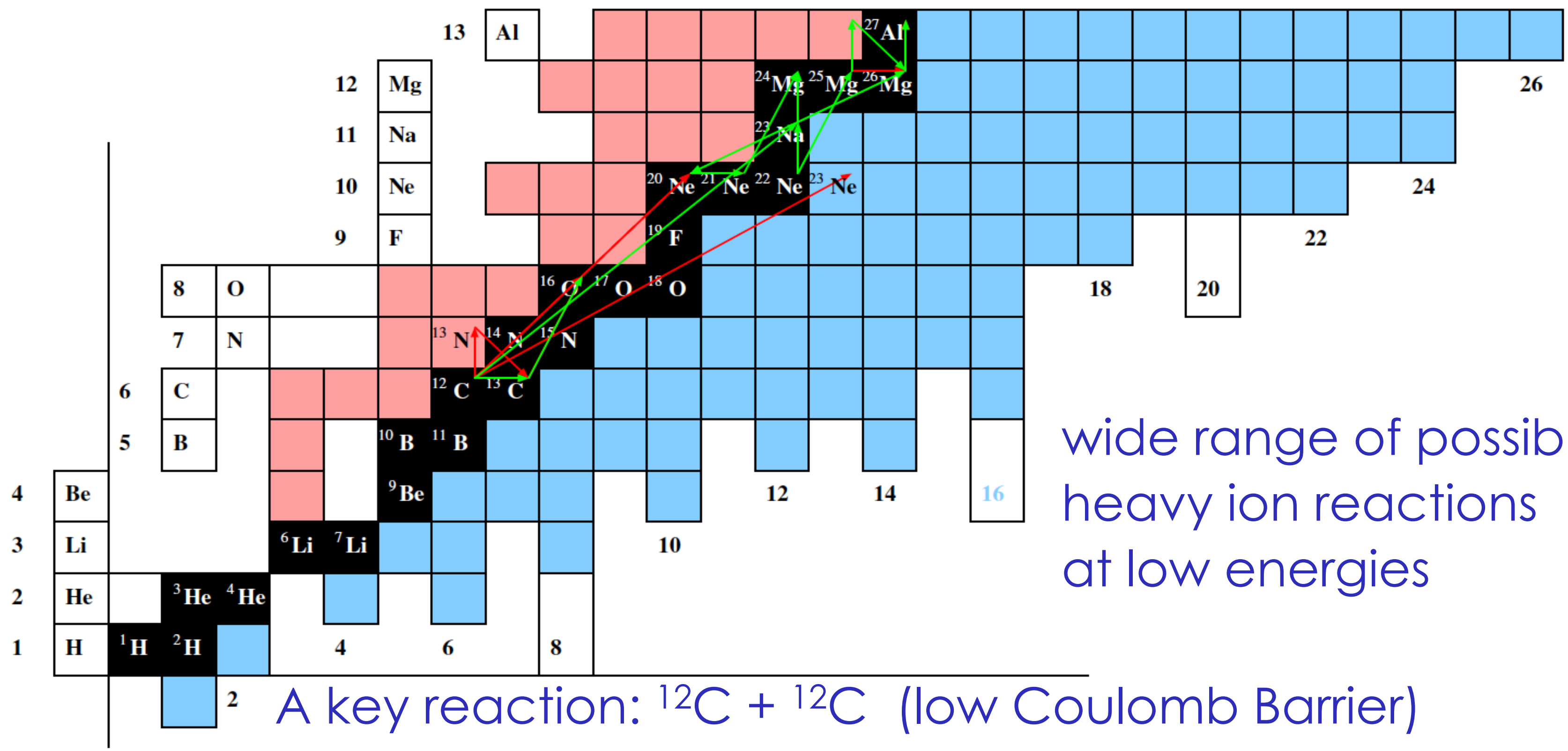
Carbon burning: a crucial phase in the stellar nucleosynthesis

The $^{12}C+^{12}C$ reaction - nucleosynthesis



wide range of possible heavy ion reactions at low energies

A key reaction: $^{12}C + ^{12}C$ (low Coulomb Barrier)

$E_G = 2.42 \times T_9^{2/3} \pm 0.75 \times T_9^{5/6}$ -> $E_G = 1.5 \pm 0.3$ MeV at 5×10^8 K

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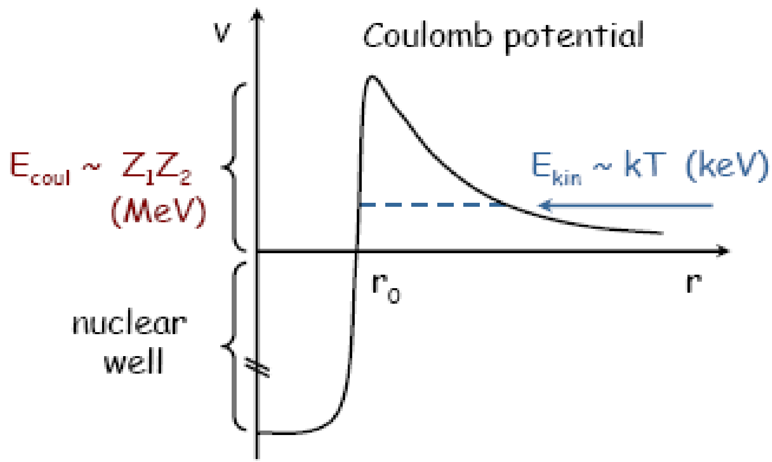
Fusion reactions at thermonuclear energies

charged particles ➡ Coulomb barrier

energy available: from thermal motion

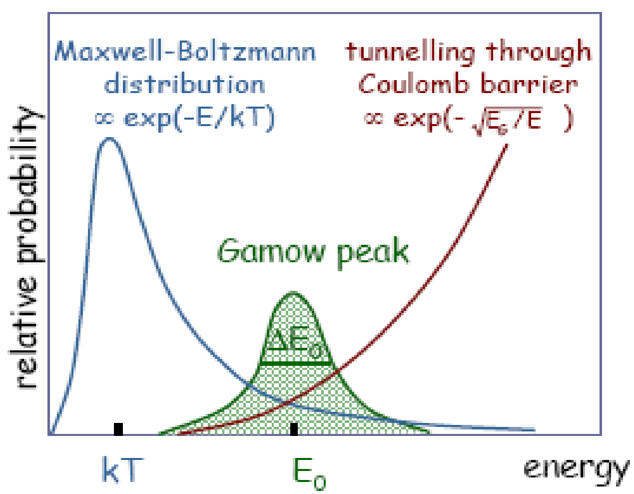


$T \sim 15\times10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

during static burnings: $kT \ll E_{coul}$

reactions occur through TUNNEL EFFECT

➡ tunneling probability $P \propto \exp(-2\pi\eta)$



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

non-nuclear origin
STRONG energy dependence

nuclear origin
WEAK energy dependence

ASTROPHYSICAL S(E)-FACTOR

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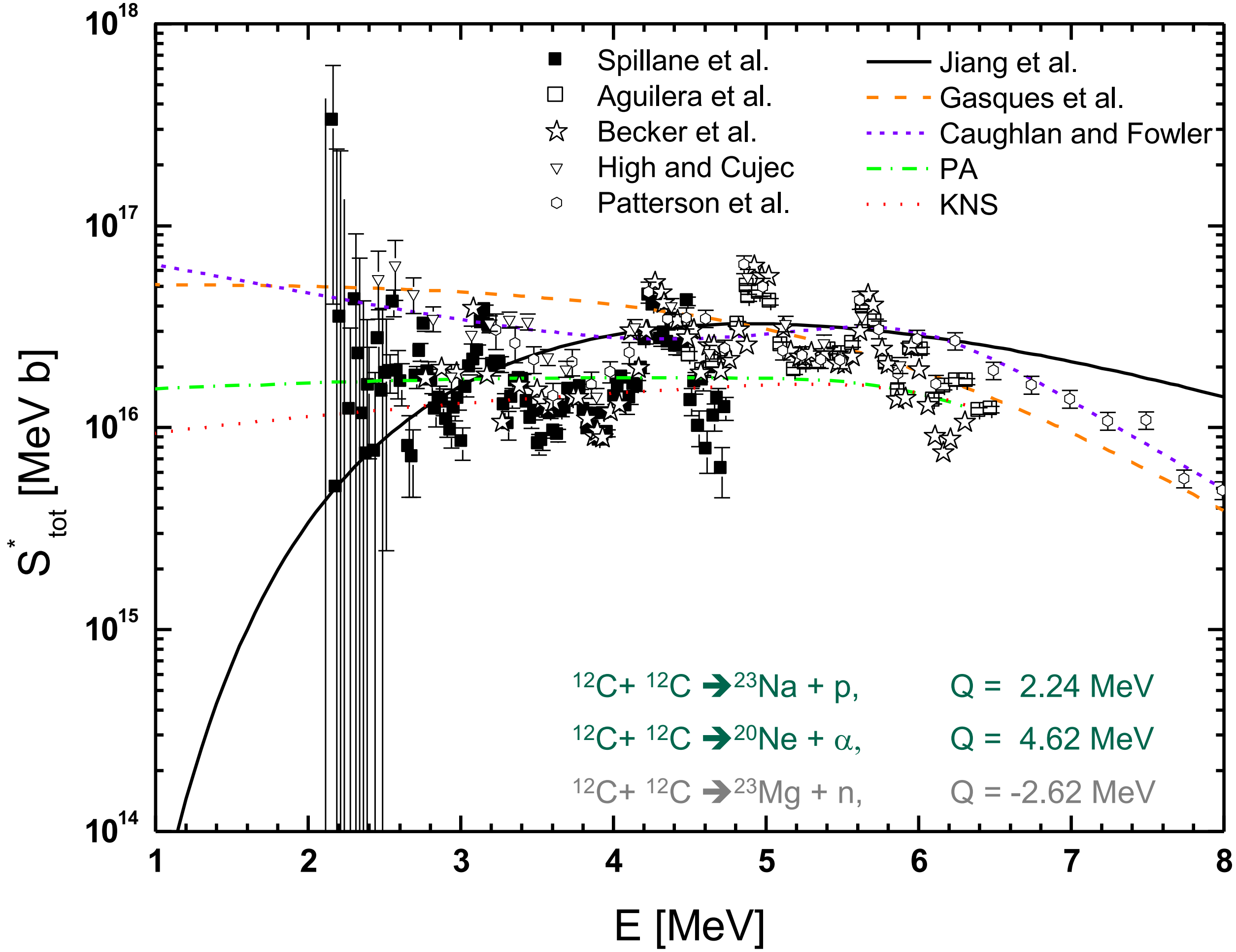
Carbon burning: $^{12}C + ^{12}C$
σ ~ nb to pb



Experimental and theoretical efforts

- \+ J.R. Patterson *et al.*, APJ 157, 367, (1969)
- \- G.J. Michaud and E.W. Vogt, PRC 5, 350, (1972)
- \+ M.G. Mazarakis and W.E. Stephens, PRC 7, 1280, (1973)
- \- R.G. Stokstad *et al.*, PRL 37, 888, (1976)
- \+ P.R. Christensen *et al.*, Nucl. Phys. A 280, 189, (1977)
- \+ M.D. High and B. Čujec, NIM A 282, 181, (1977)
- \+ K.-U. Kettner *et al.*, PRL 38, 377, (1977)
- \+ K.A. Erb *et al.*, PRC 22, 507, (1980)
- \+ H.W. Becker *et al.*, Z. Phys. A 303, 305, (1981)
- \- Y. Suzuki and K.T. Hecht, Nucl. Phys. A 388, 102. (1982)
- \+ B. Čujec *et al.*, PRC 39, 1326, (1989)
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- \+ L. Barrón-Palos *et al*, Nucl. Phys. A 779, 318, (2006)
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- \+ C.L. Jiang *et al.*, PRC 75, 015803, (2007)
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- \+ C.L. Jiang *et al.*, NIM A 682, 12, (2012)
- \+ X. Fang *et al.*, Jour. Phys. 420, 012151, (2013)
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- \- A.A. Aziz *et al.*, PRC 91, 015811, (2015)
- \+ B. Bucher *et al.*, PRL 114, 251102, (2015)
- \+ A. Tumino *et al.*, EPJ Conf. 117, 09004, (2016)

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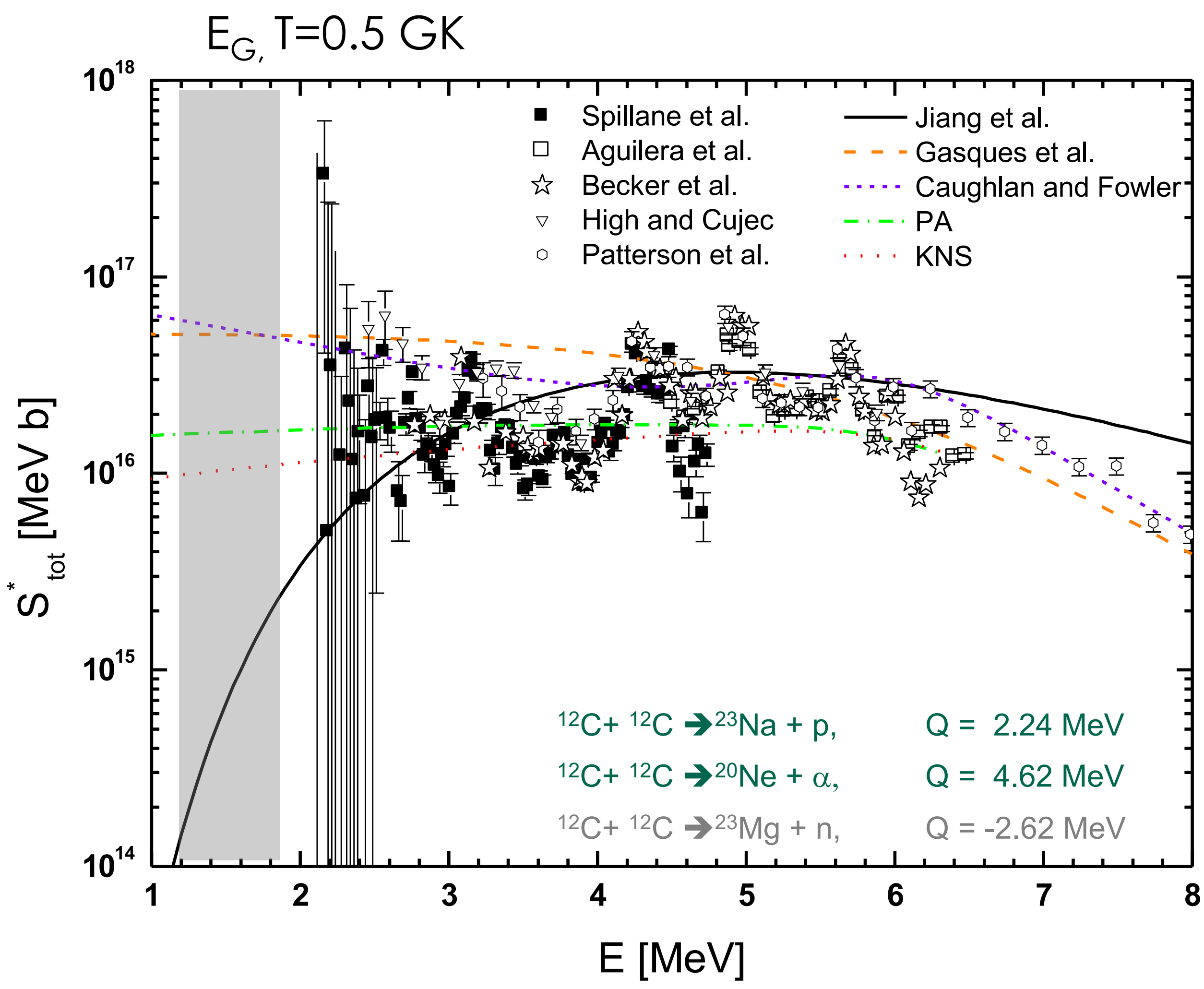
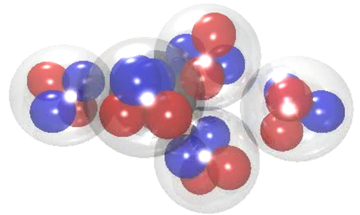
Carbon burning: $^{12}C + ^{12}C$

σ ~ nb to pb





- Single particles or γ
- Extremely sensitive to background
- Extrapolations with very different trends
- Crucial role of resonances, impact on the reaction rate ?

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What our studies of reactions may bring

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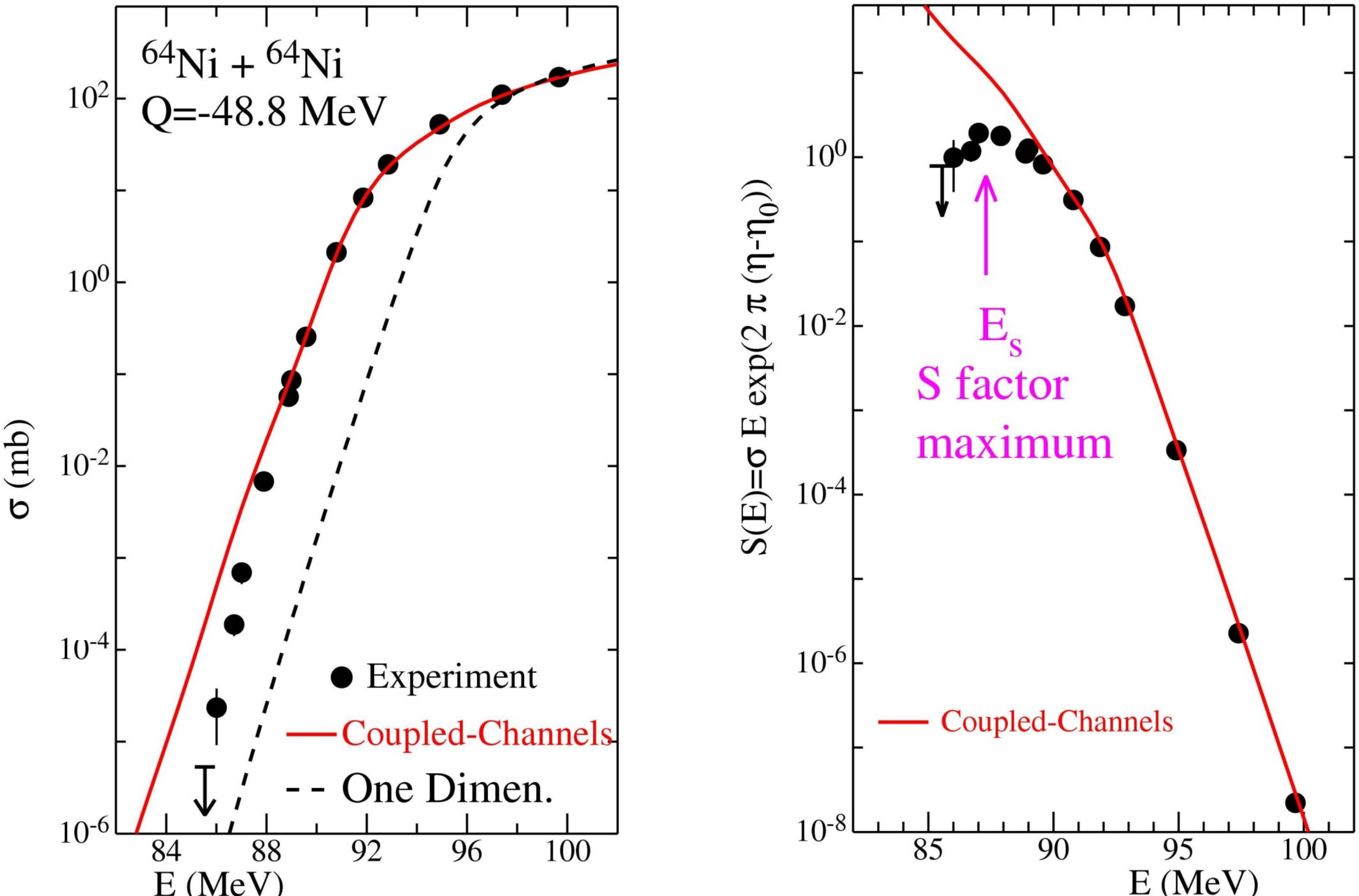
Fusion hindrance / medium mass systems

C.L.Jiang et al., Phys.Rev. Lett.89,052701(2002);Phys.Rev.Lett.93,012701(2004)



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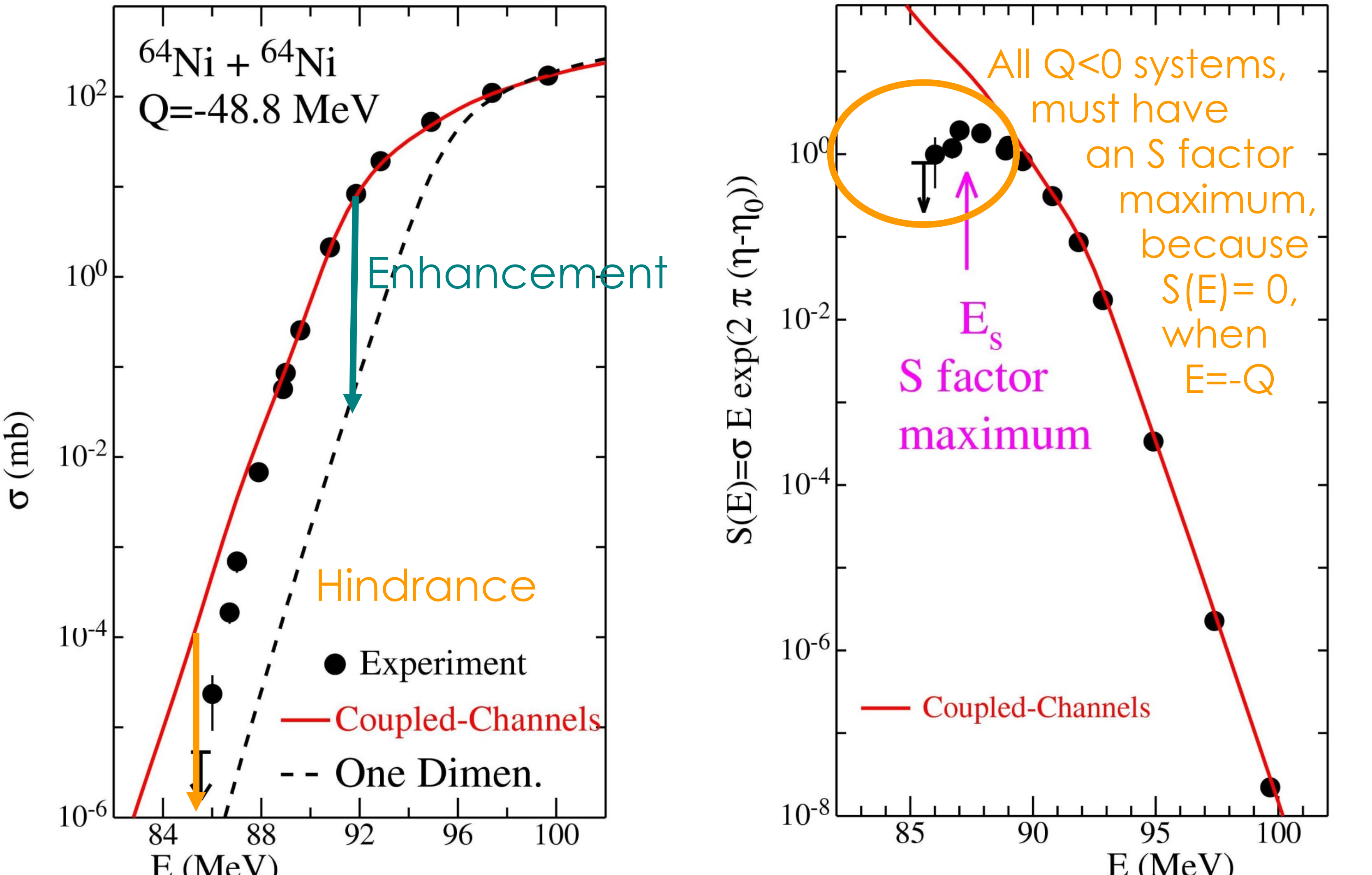

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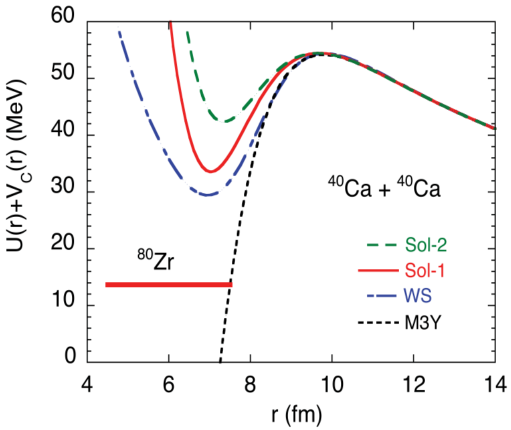
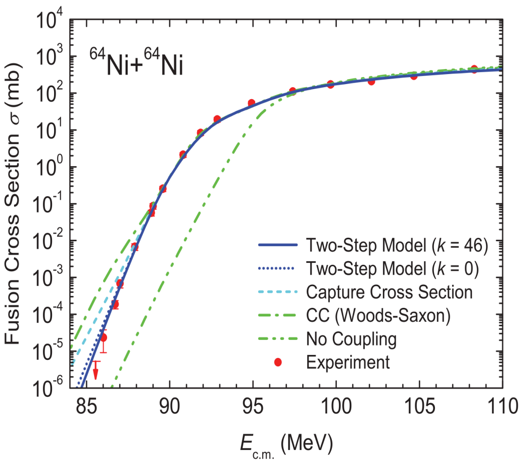
Theory – fusion hindrance

Saturation property of nuclear matter
(double-folding potential + repulsive core / M3Y + rep.)
S.Misicu et al., Phys. Rev. Lett. 96 (2006).

Adiabatic potential model (two steps model: capture in a 2 body potential pocket / penetration of one body potential -> compound nucleus state)
T.Ichikawa, K.Hagino and A.Iwamoto et al., Phys. Rev. C75 (2007)
Phys. Rev. Lett. 103 (2009).

Pauli principle (C. Simenel et al., Phys. Rev. C (2018))





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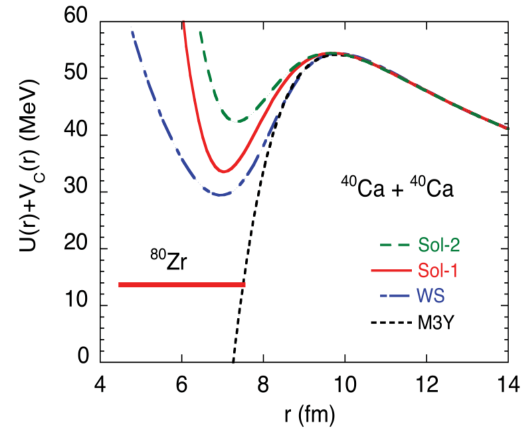

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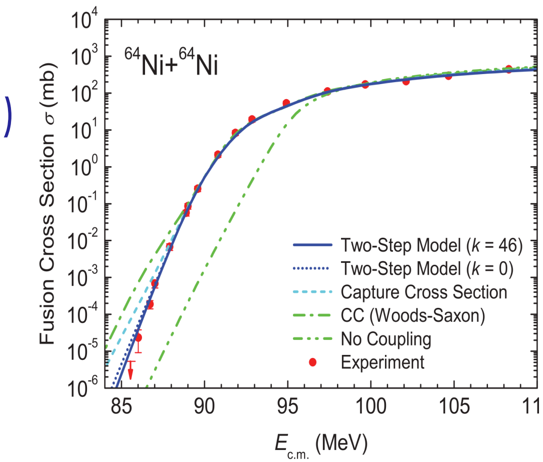

Pauli principle (C. Simenel et al., Phys. Rev. C (2018))

Nuclear matter effect ⇒ impact on light systems of astrophysical interest

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What our knoweledge of structure may bring

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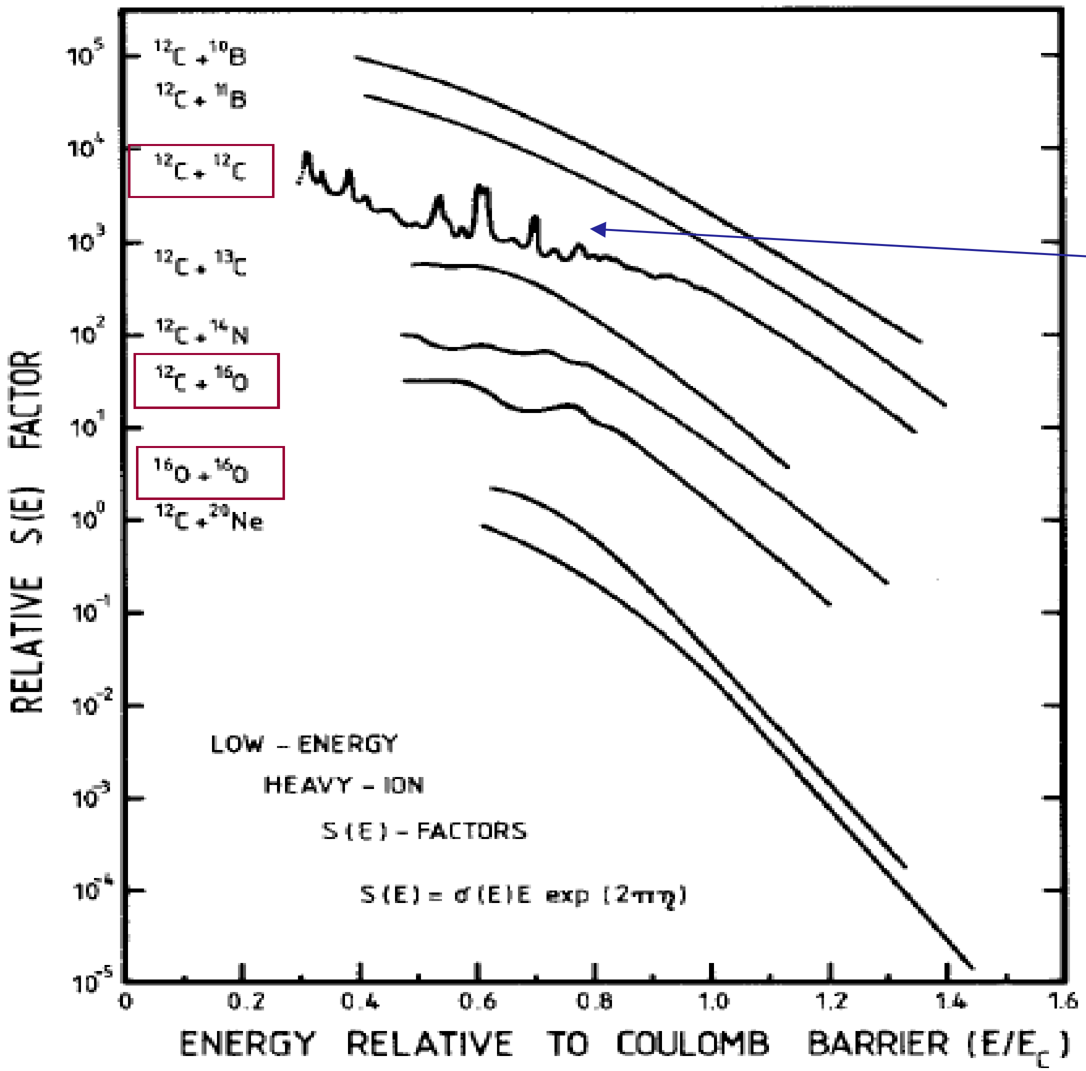
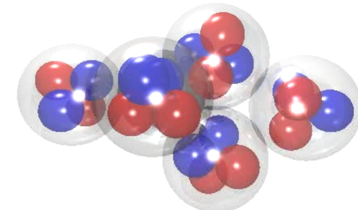
Cross-sections for some light systems at subcoulomb energies





R. Stokstad et al., Phys.Rev.Lett. 37 (1976)

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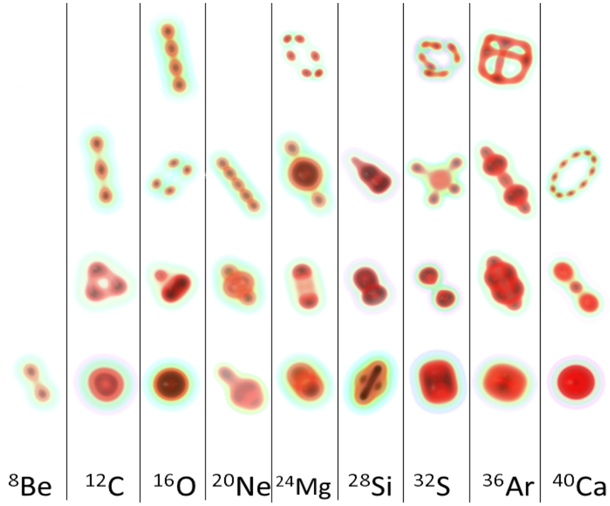
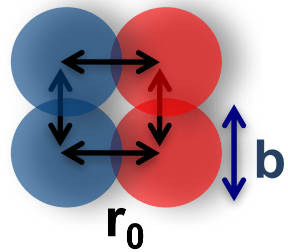
Theory – cluster resonances

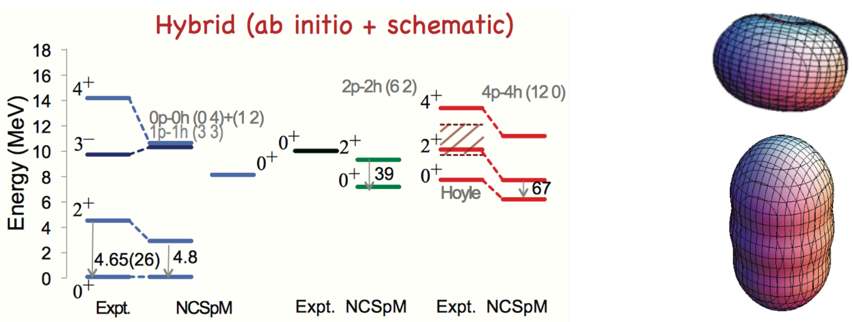




Liquid, cluster, cristal

- $\alpha_{loc} = b/r_0$
- energy

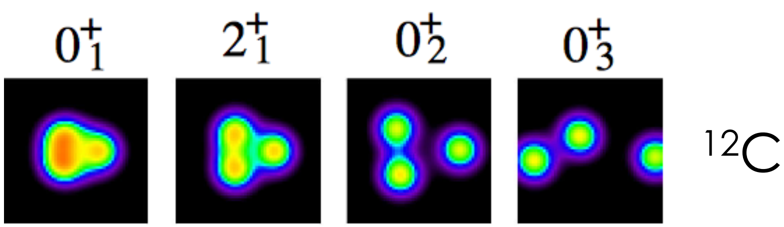
J.-P. Ebran et al, PRC 90(2014)054329, / Nature 487(2012)341



(a) (b)

Symmetry adapted no-core SM

Dreyfuss et al., PRL 2013 / Launey et al., J.of. Phys. CS 2014



AMD calculations

Y. Kanada-En'Yo et al., Prog. Theor. Phys. (2012)

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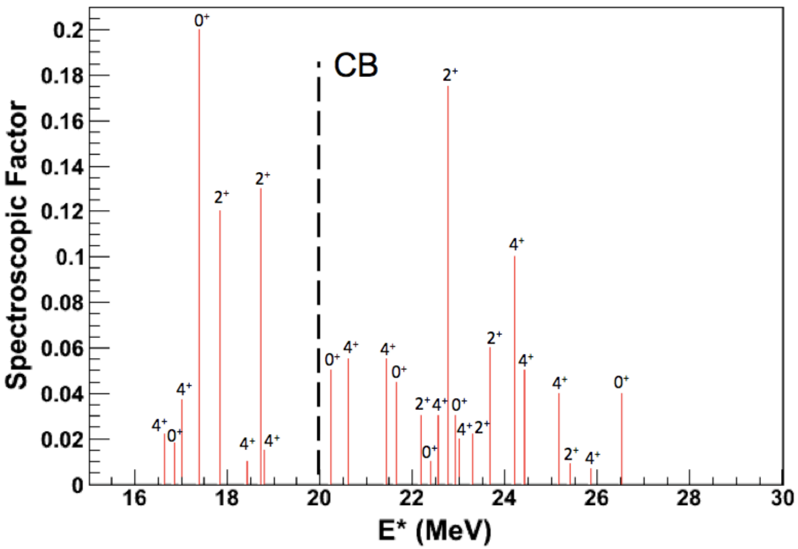
Theory – cluster resonances



Sub-Coulomb $^{12}C + ^{12}C$ resonances in ^{24}Mg in a microscopic $^{12}C+^{12}C, \alpha+^{20}Ne$, $^{8}Be+^{16}O$ cluster basis

Adapted from Y. Suzuki and K.T. Hecht, Nucl. Phys. A 388, 102 (1982).

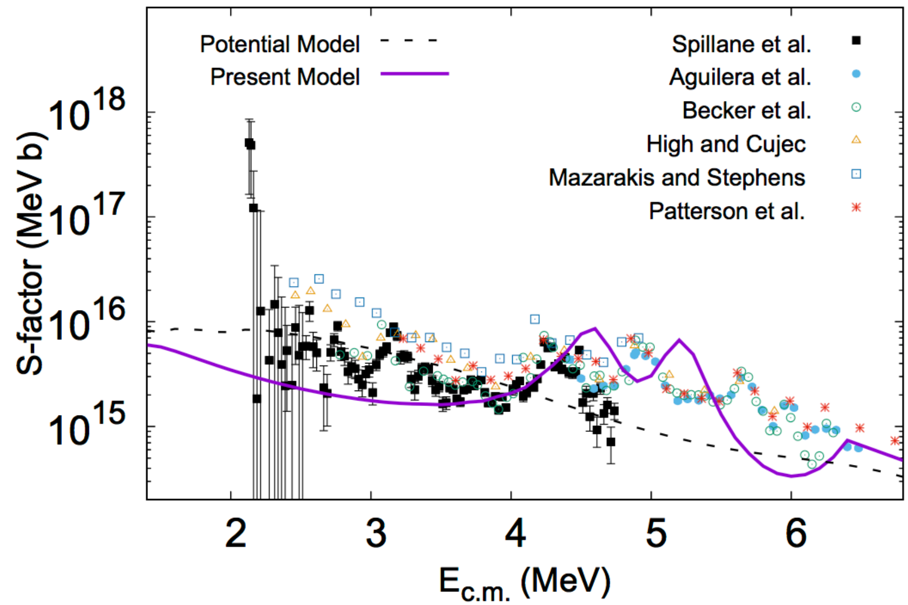


FIG. 5. The astrophysical S-factor excitation function for $^{12}C + ^{12}C$. Measurements [2–7] (symbols) are compared to model calculations (dashed and solid lines), indicating that molecular structure and fusion are interconnected.

A. Diaz Torres and M. Wiescher, Phys. Rev. C 97 (14.05.2018)

Approaches to tackle the $^{12}C+^{12}C$ fusion reaction

… measuring excitation functions down to the pb range

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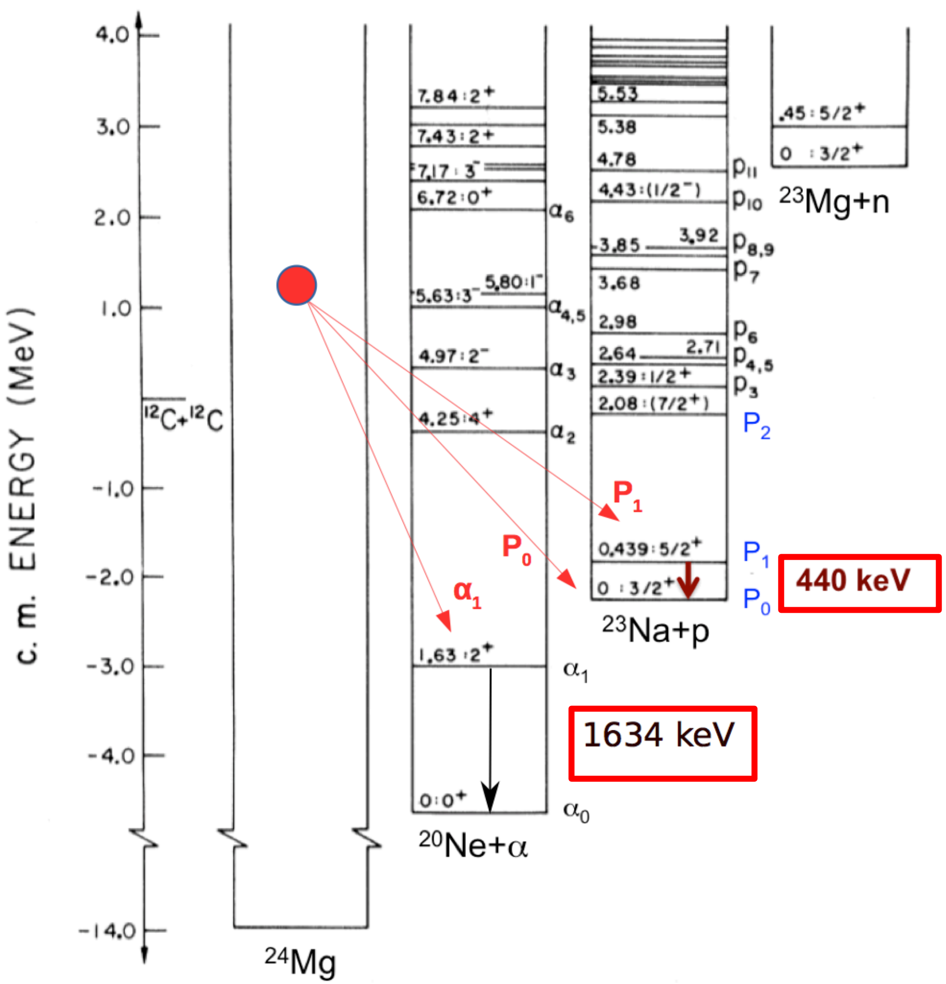
The STELLA project

Mobile station for the measurement of fusion cross-sections of astrophysical interest



Challenges

- ‘Clean measurement’
  γ-particle coincidences :
  $\text{Efficiency}_{Tot} = \varepsilon_{\gamma} \times \varepsilon_{part}$
- Extremely small cross-section
  Thin target under high intensity beam
  Extended data taking
- Normalization
  Carbon build-up

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$^{12}C+^{12}C$ cross-sections , sources of uncertainties

1) Backgrounds:

Detection of charged particles, p and α:

$^{12}C + H \longrightarrow p$ and $^{12}C+D \longrightarrow p$ or d

Detection of γ-rays:

$^{12}C+H \longrightarrow \gamma$ and $^{12}C+D \longrightarrow \gamma$;

cosmic rays and room backgrounds

2) Thick targets measurements:

Taking the difference of two measurements at different energies.

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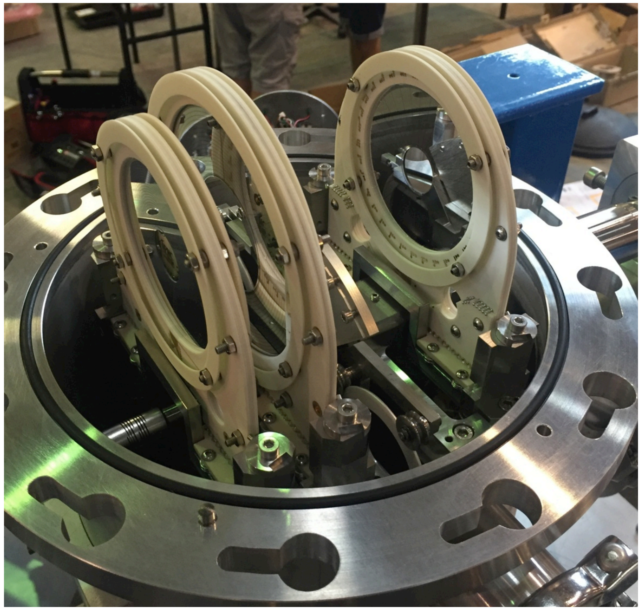
Particle and gamma detection



- Annular silicon detectors
- Low outgassing PCB
- New pin connectors / noise reduction
- Angular coverage $\Delta\Omega$ ~ 24 % of 4π.

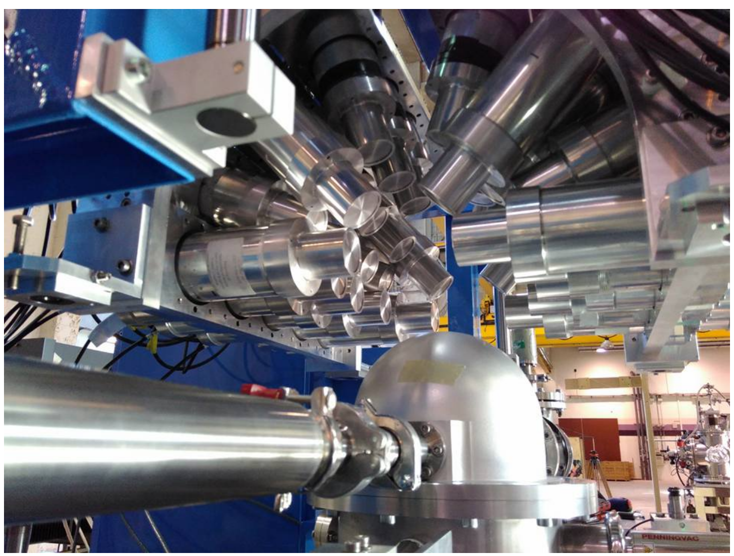


Photo : M. Heine

- 36 $LaBr_3$ detectors
  Timing selection of p and α
- Self activity
- ε = 8% @ 440 keV

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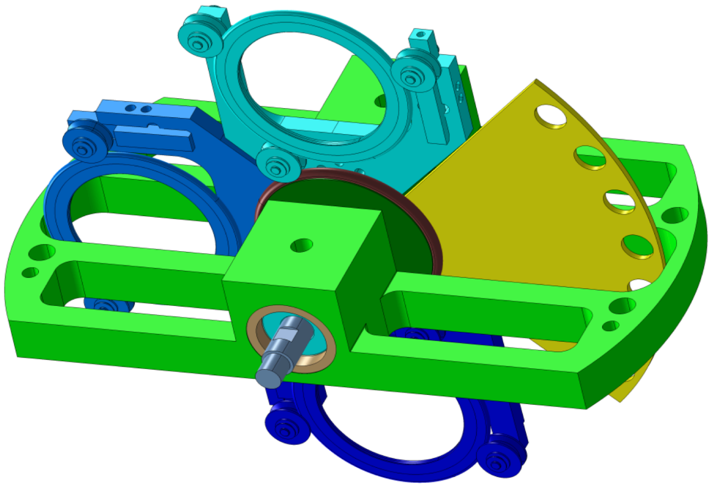
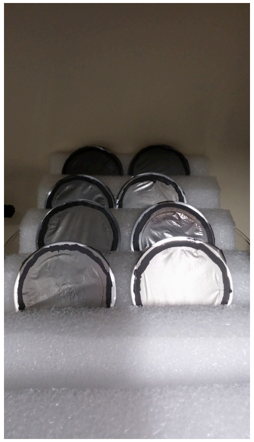
Target developments

and vacuum



IPHC and GANIL collaboration

- Cryogenic pumping
- Fixed + rotating target system (> 1000 rpm)
- I > 1 pμA



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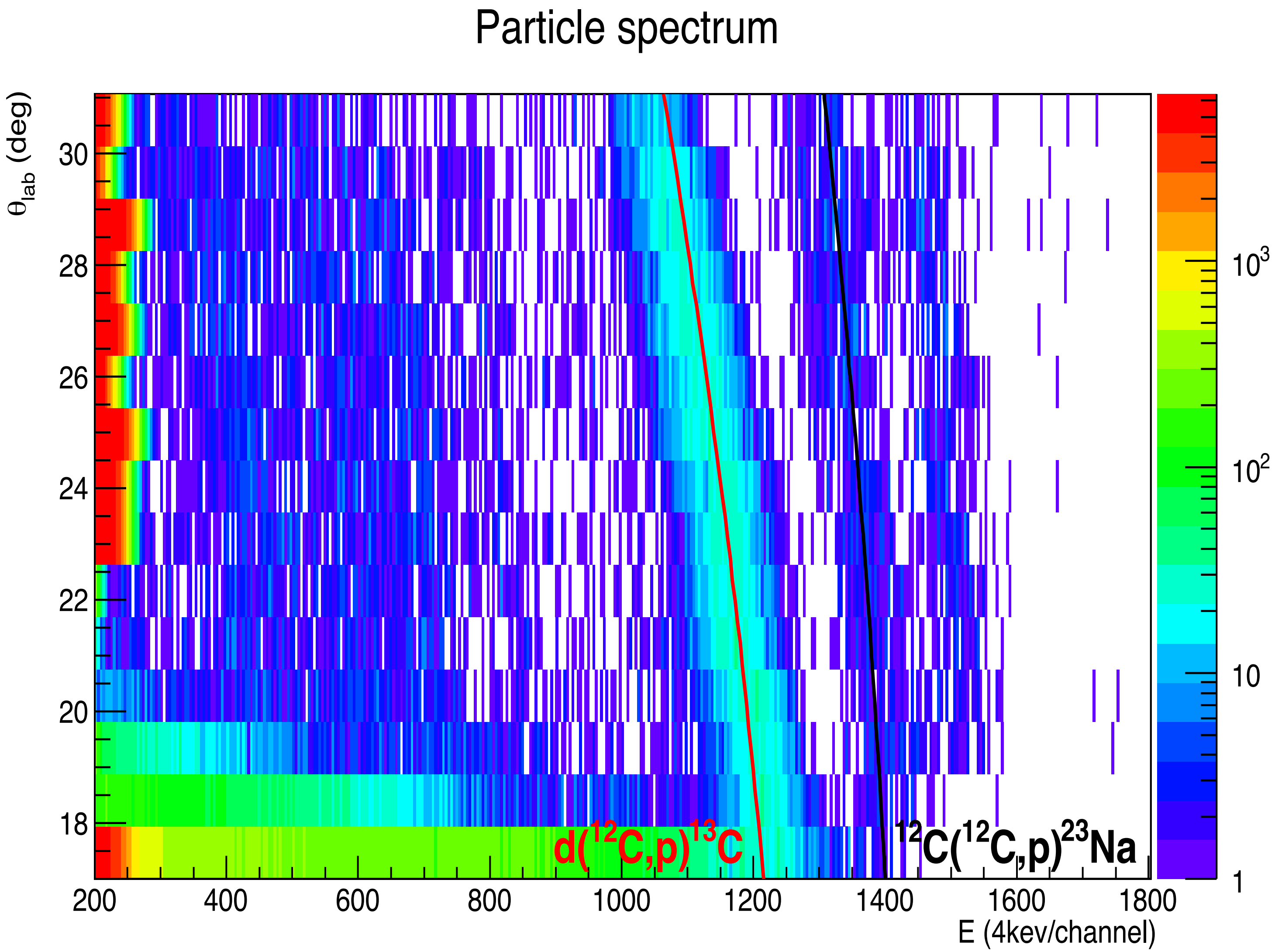
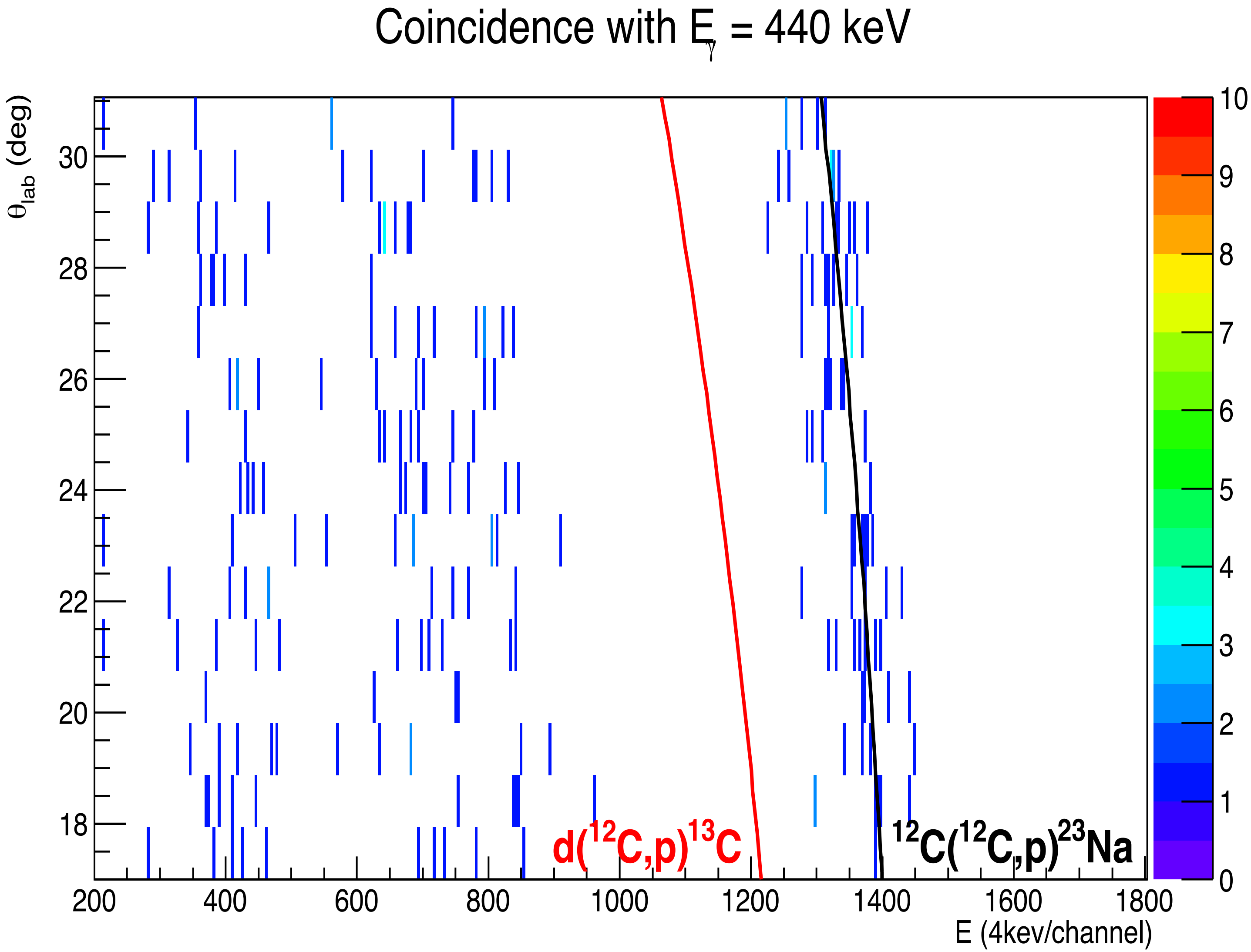
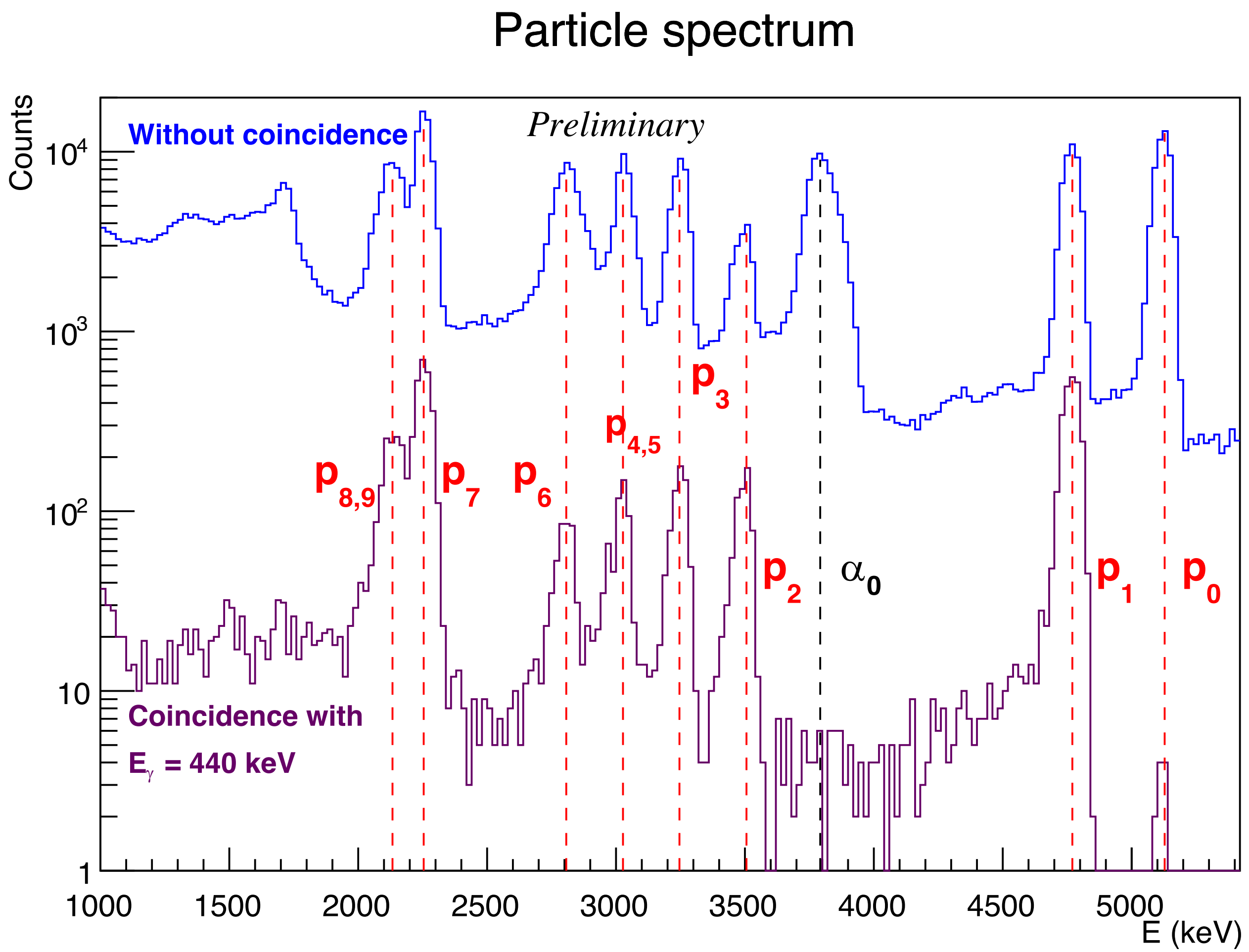
Coincidences



Coincidences

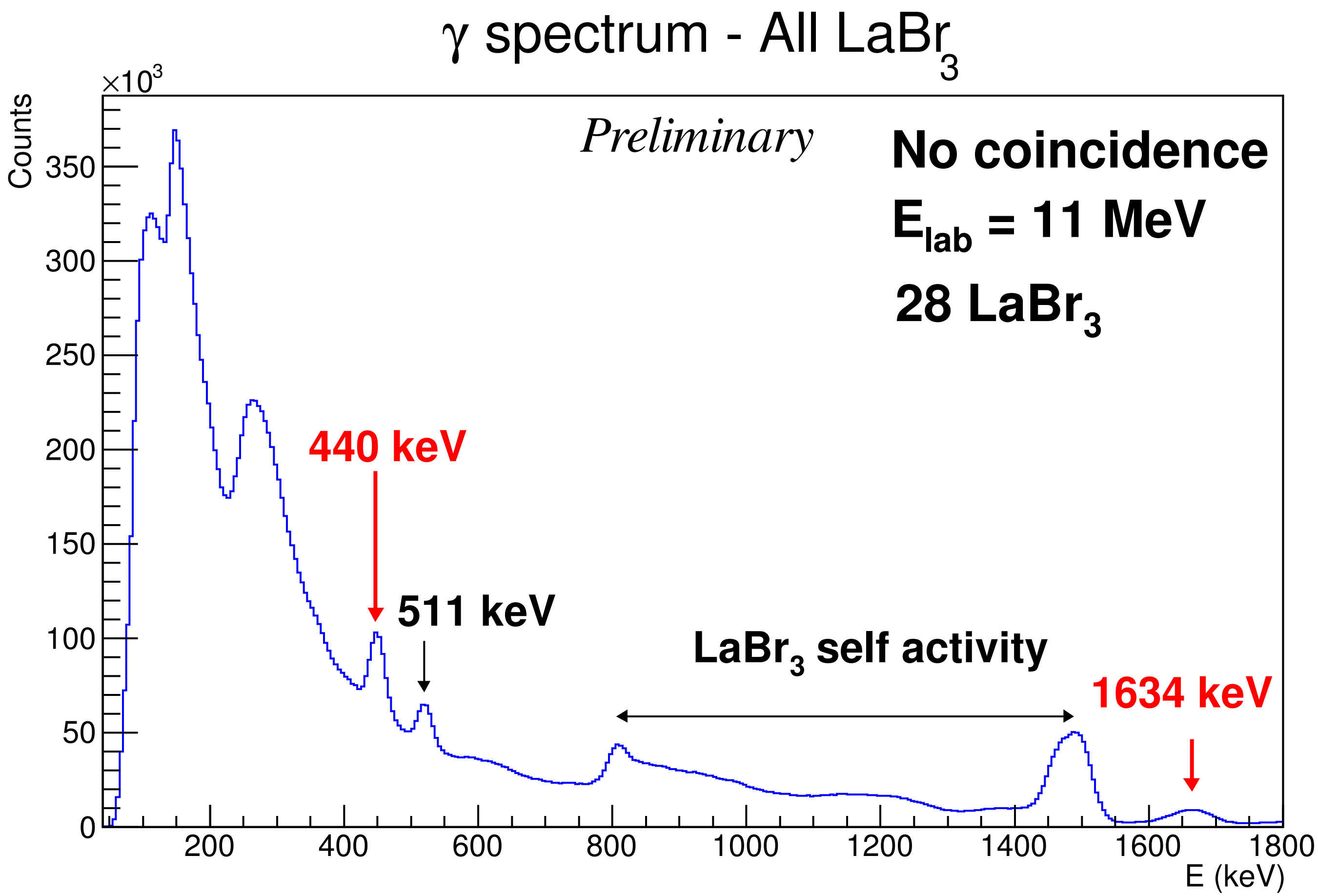


Coincidences

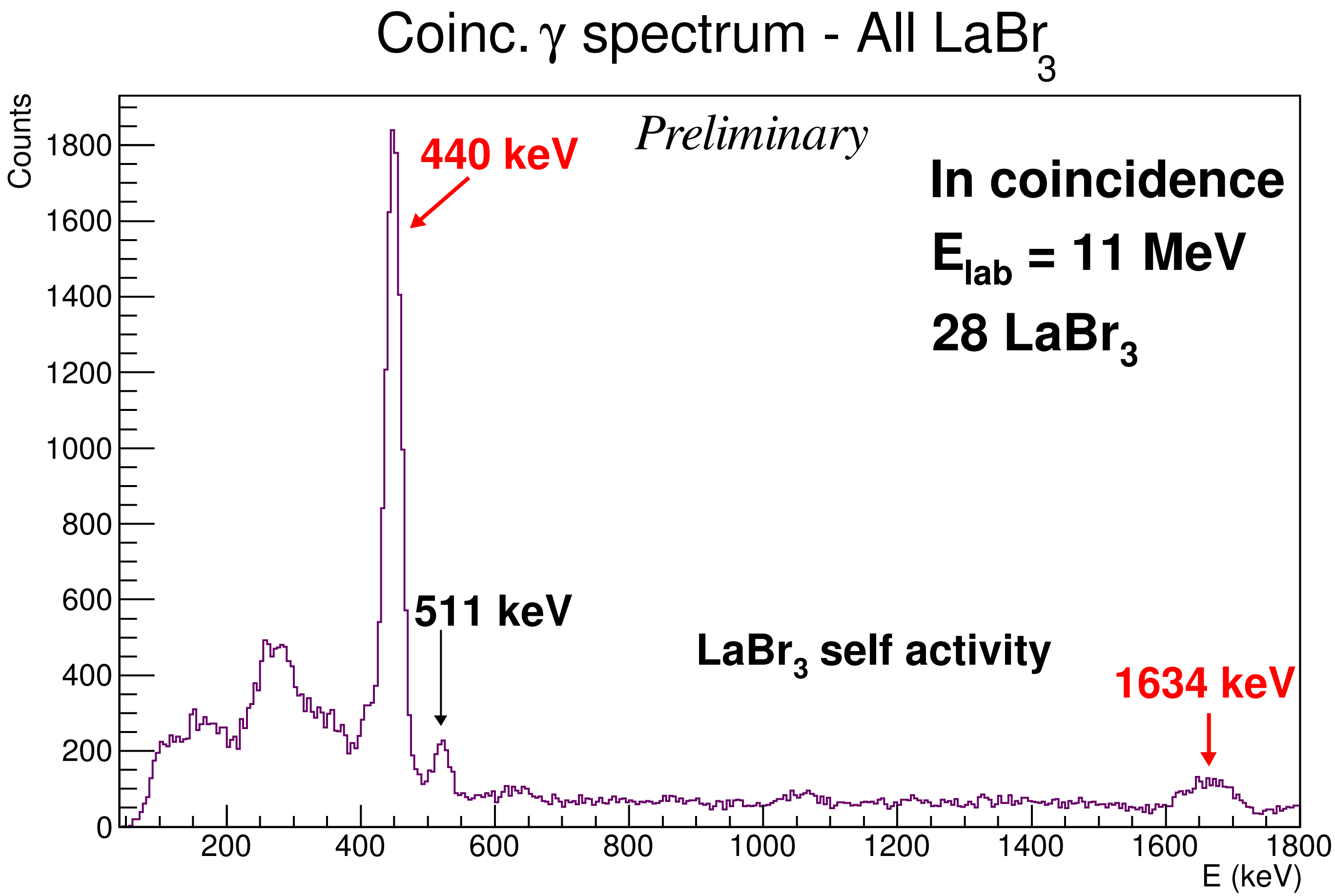


Gate on E_{γ} = 440 keV

Suppression of α_0 and p_0 / $\varepsilon_{440\ keV}$ = 6%



Self activity & γ of interest from $^{12}C+^{12}C$ fusion



Coincidence with 1 particle : γ from fusion

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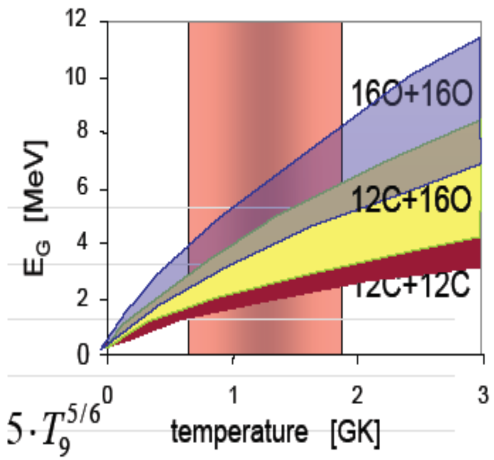
Conclusions



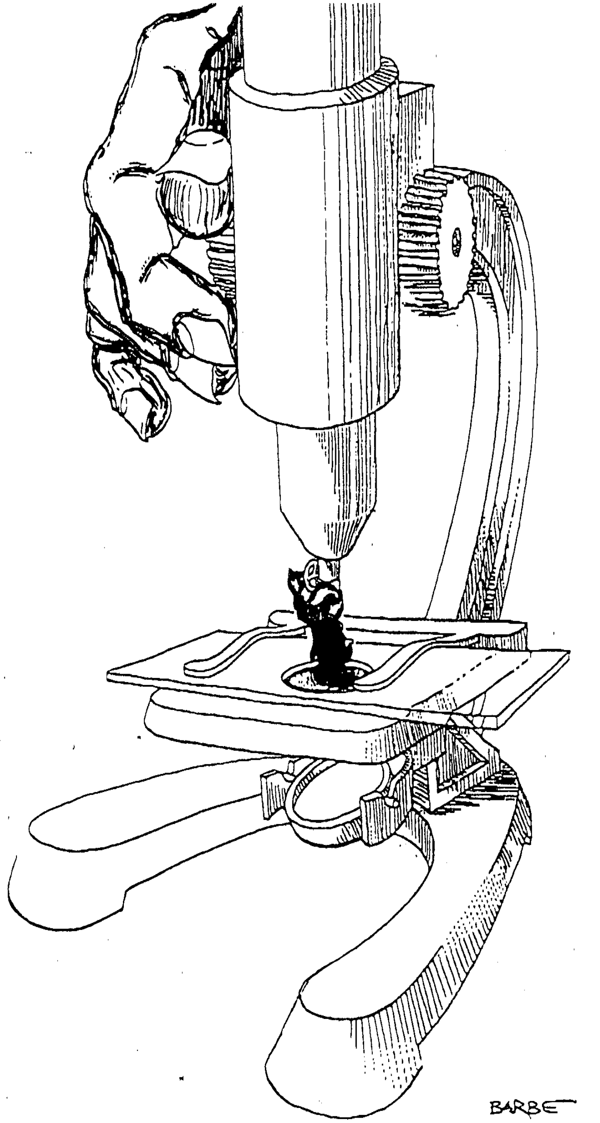
I. Importance of direct measurements

II. Only a few systems will be measured
-> importance of theory of structure and reactions

III. Measurements in the Gamow window on the way
-> may need new technical developments, ideas …

IV. Complementary measurements

Thanks !



Courtesy: M. Arnould

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