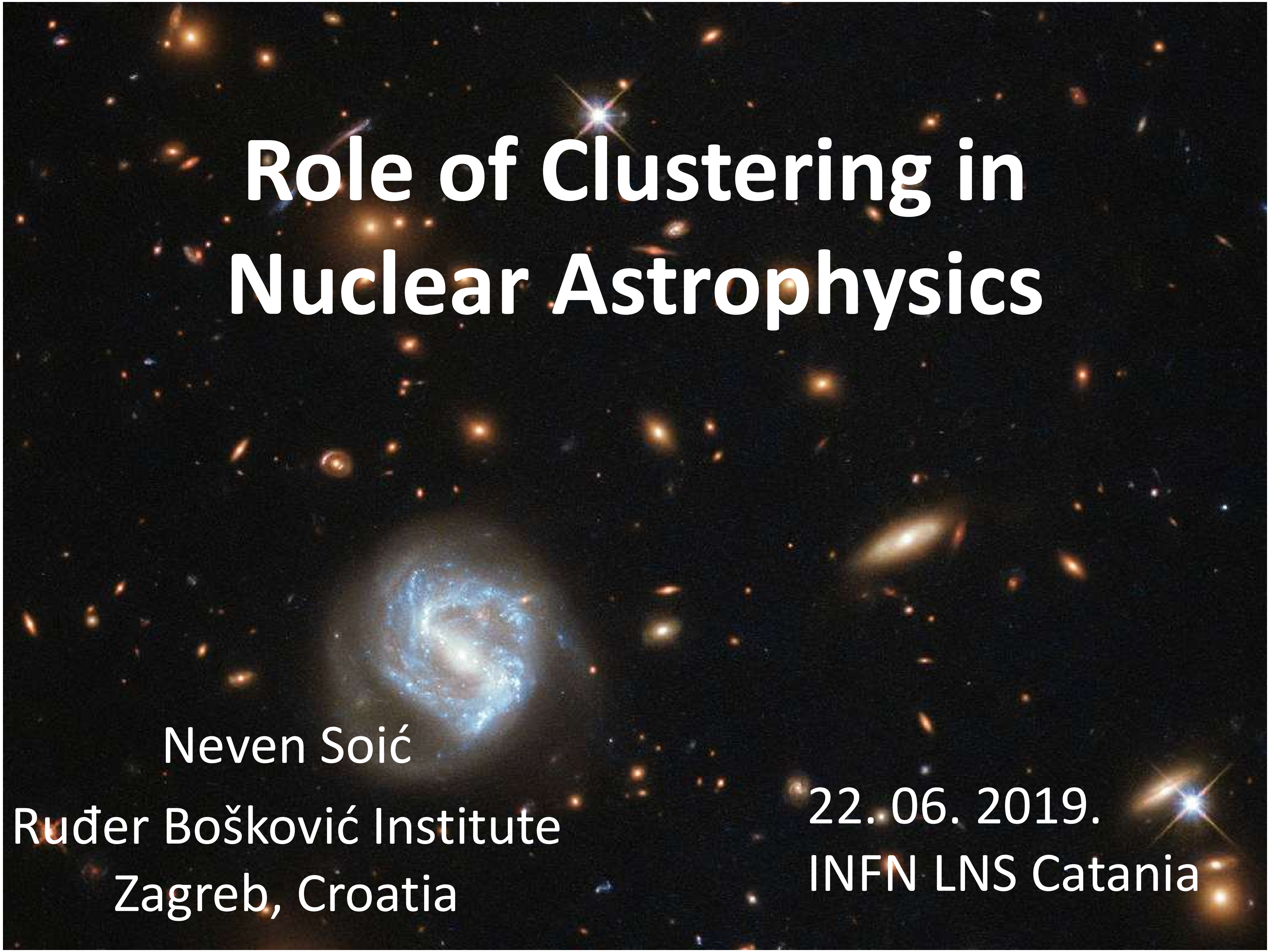

Role of Clustering in Nuclear Astrophysics

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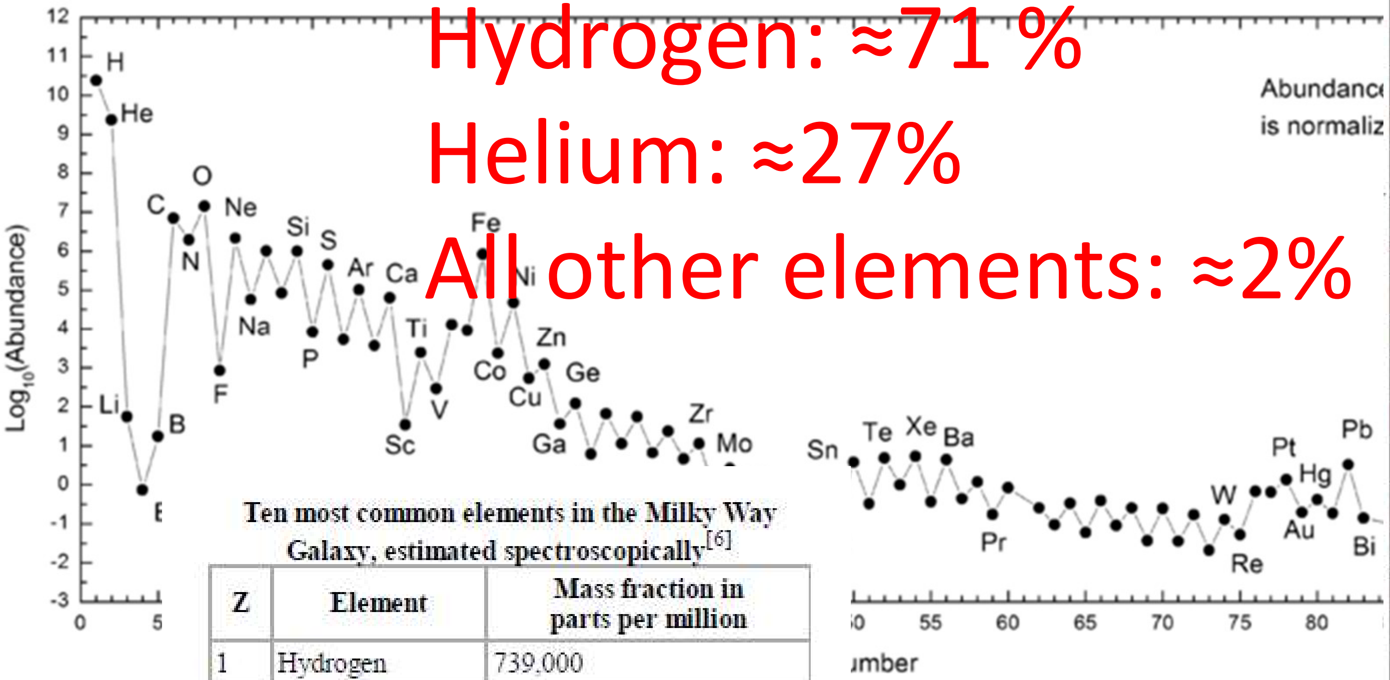
22. 06. 2019.
INFN LNS Catania

Outline

- Nuclear structure and reaction dynamics
- Genesis of the elements
- Triple α fusion
- The (α,γ) reactions on ^{12}C and ^{16}O
- The (α,n) reactions
- Carbon – carbon fusion
- Experimental techniques and methods
- Summary

Chemical composition of visible matter

Solar system



Average for the Universe:

Hydrogen: ≈71 %

Helium: ≈27%

All other elements: ≈2%

Ten most common elements in the Milky Way Galaxy, estimated spectroscopically[6]

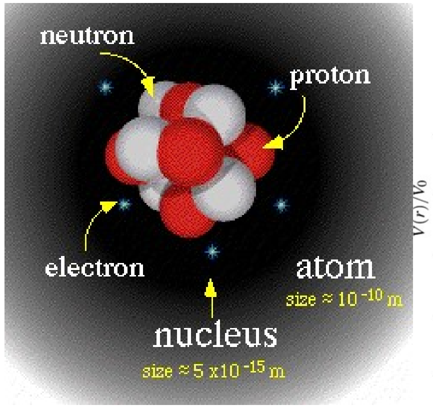
Z	Element	Mass fraction in parts per million
1	Hydrogen	739,000
2	Helium	240,000
8	Oxygen	10,400
6	Carbon	4,600
10	Neon	1,340
26	Iron	1,090
7	Nitrogen	960
14	Silicon	650
12	Magnesium	580
16	Sulfur	440

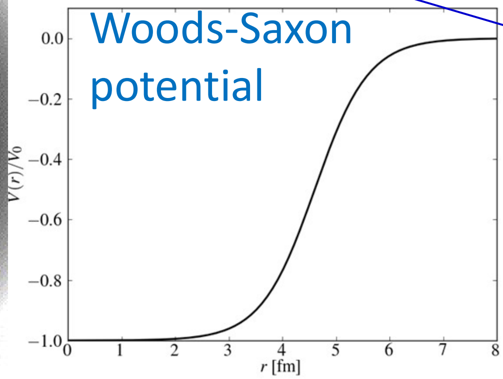
Most abundant isotopes in the Solar System[1]

Isotope	Mass fraction in parts per million	Atom fraction in parts per million
Hydrogen-1	705,700	909,964
Helium-4	275,200	88,714
Oxygen-16	5,920	477
Carbon-12	3,032	326
Nitrogen-14	1,105	102
Neon-20	1,548	100
Other Elements	3,879	149
Silicon-28	653	30
Magnesium-24	513	28
Iron-56	1,169	27
Sulfur-32	396	16
Helium-3	35	15
Hydrogen-2	23	15
Neon-22	208	12
Magnesium-26	79	4
Carbon-13	37	4
Magnesium-25	69	4
Aluminum-27	58	3
Argon-36	77	3
Calcium-40	60	2
Sodium-23	33	2
Iron-54	72	2
Silicon-29	34	2
Nickel-58	49	1
Silicon-30	23	1
Iron-57	28	1

Structure of atomic nuclei

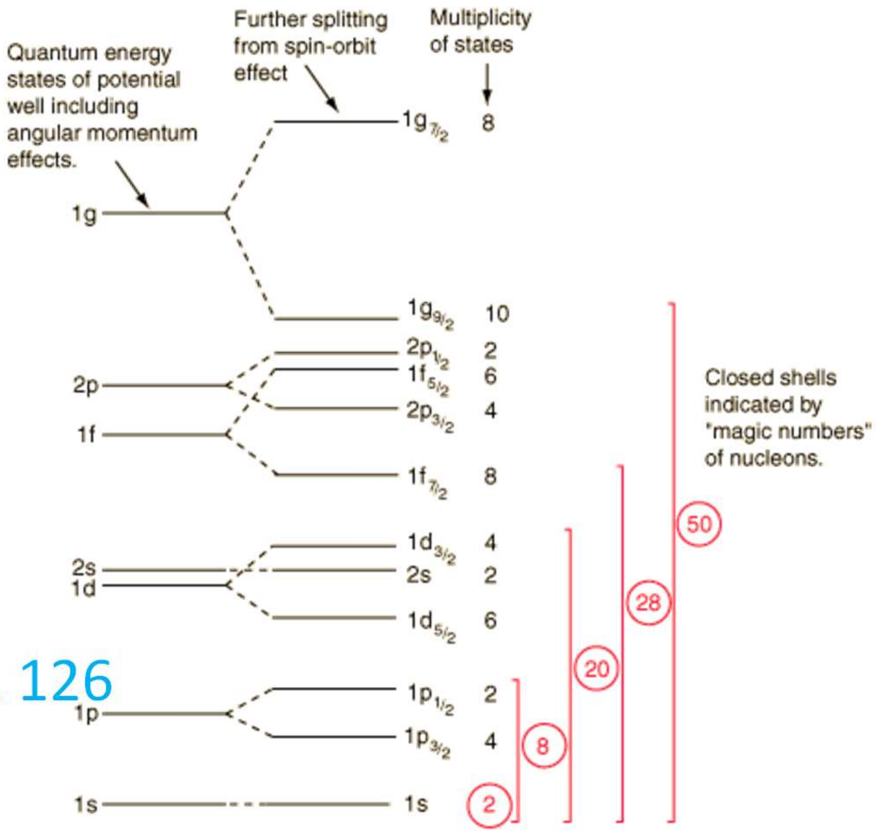
- Fundamental forces: strong, weak, electromagnetic & gravitational





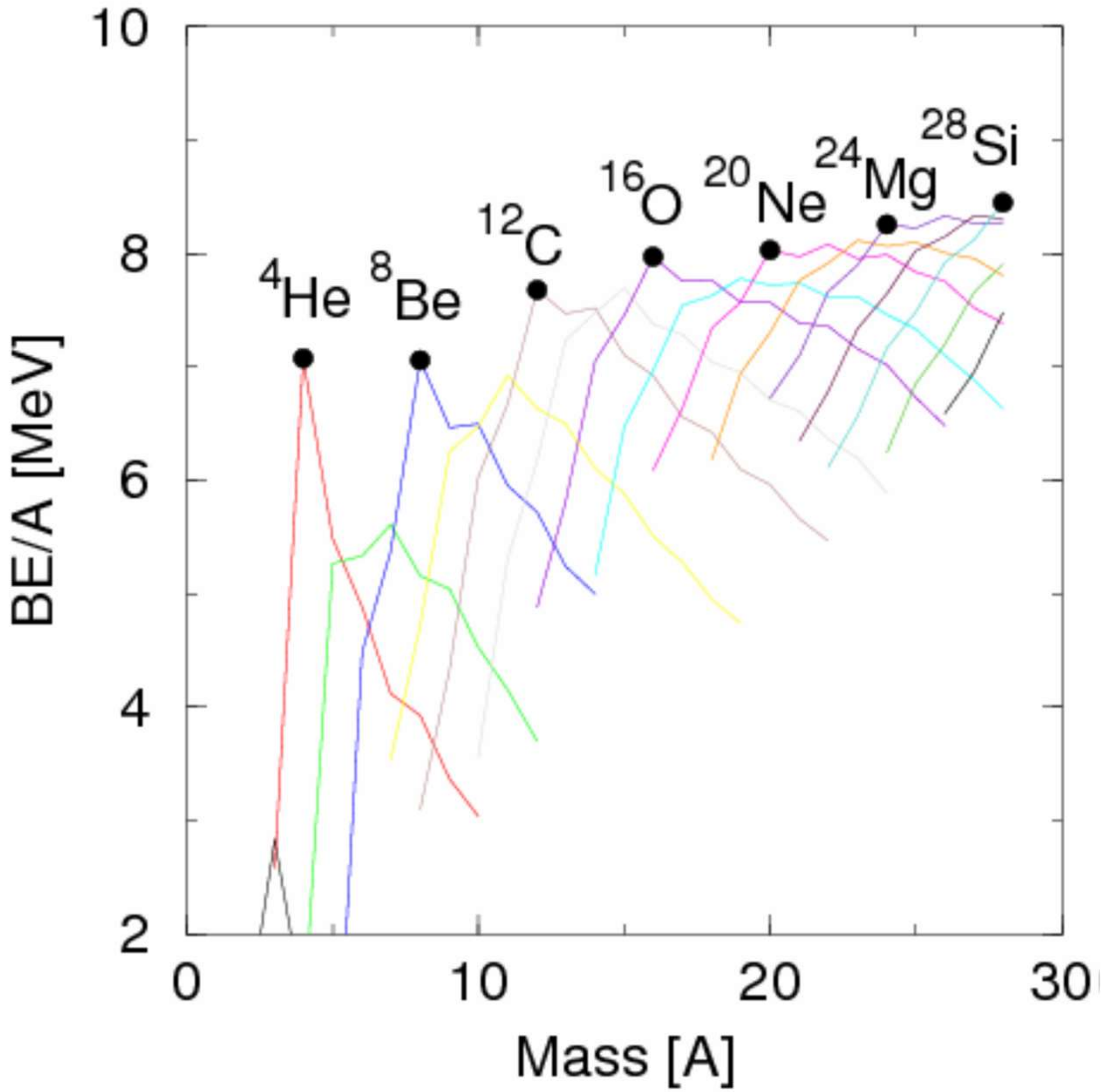
atomic nucleus

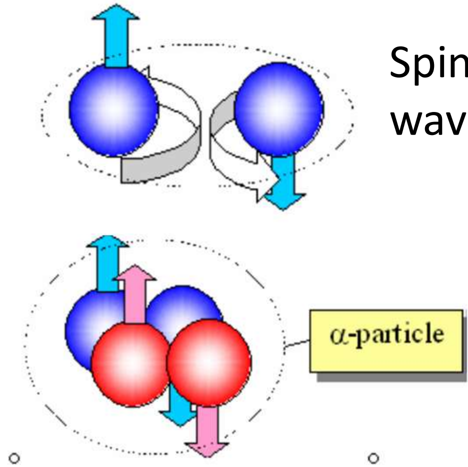
- Nucleus is quantum system: specific states depending on intrinsic nucleus energy



- Shell model: spherical systems
- magic numbers: 2, 8, 20, 28, 50, 82, 126

What evidence is there for correlation effects in nuclei?



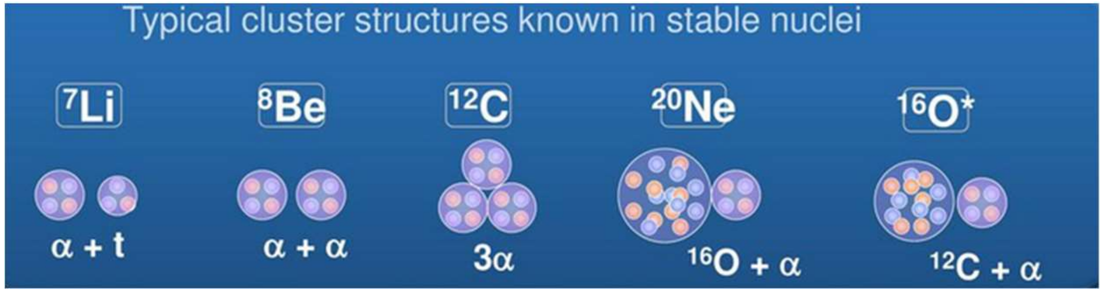


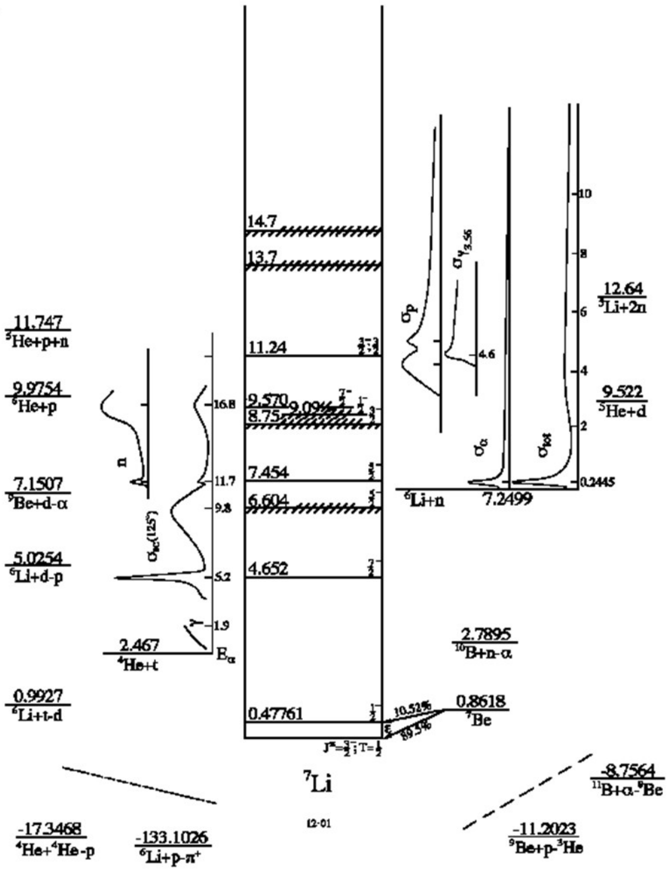
Spin-part of wave-function

Even-even nuclei have spin zero ground states

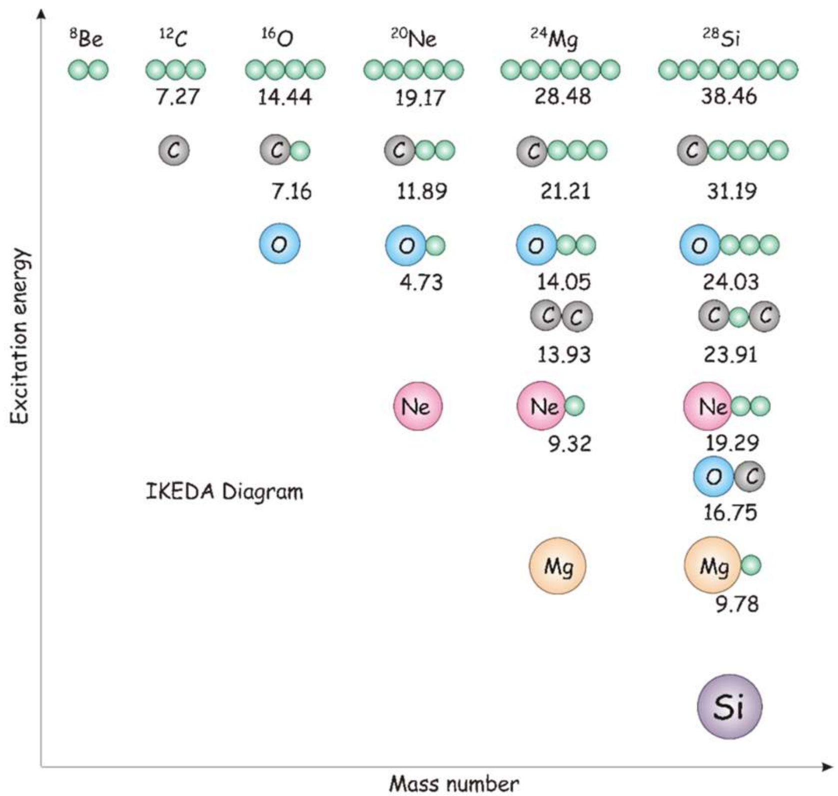
Clustering

- many-body correlations
- 2-or 3-centre structures
- pronounced in light nuclei
- basic unit is α-particle - fermions ↔ boson

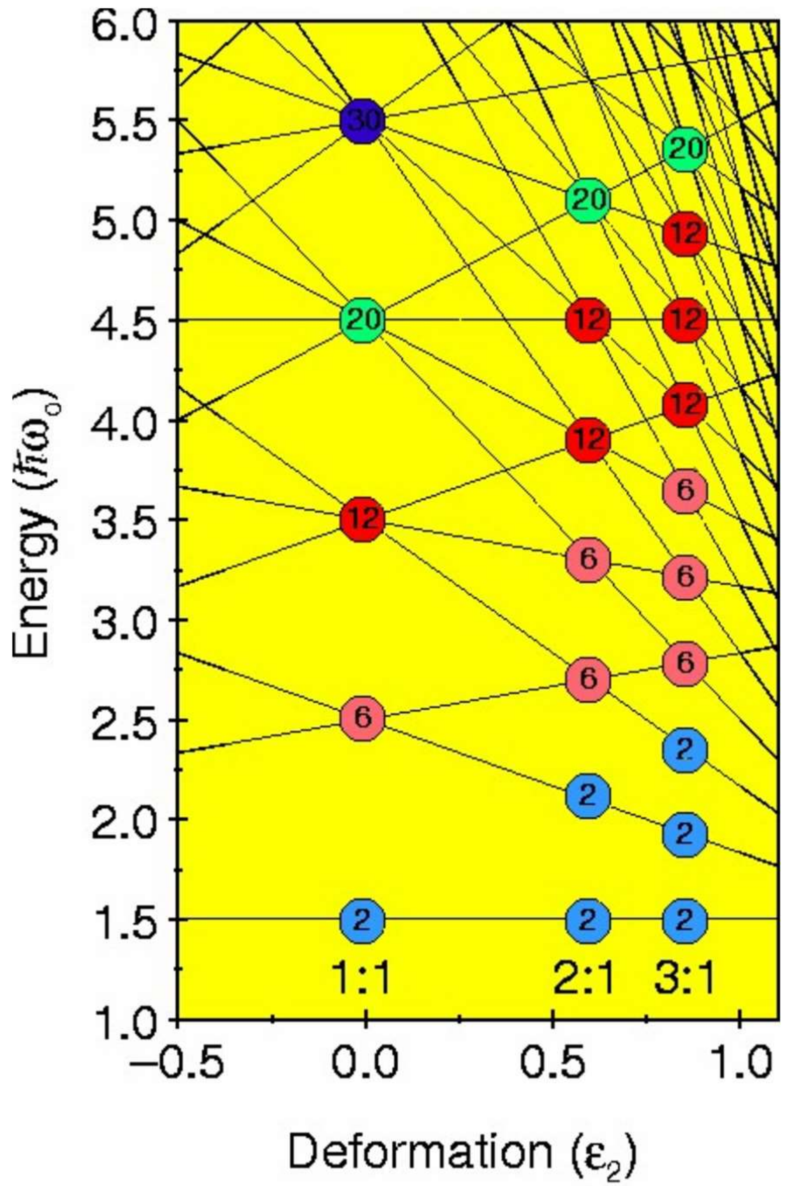


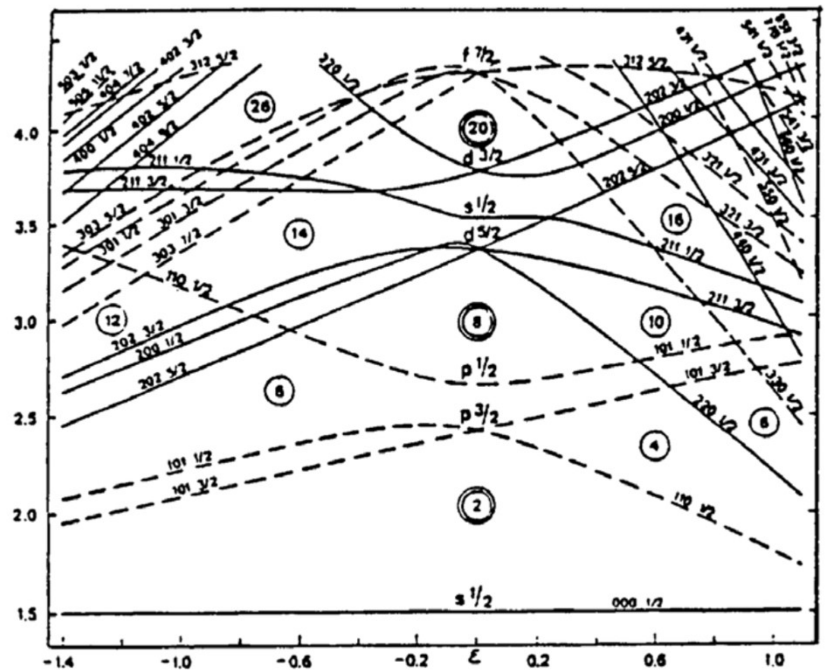


Ikeda diagram

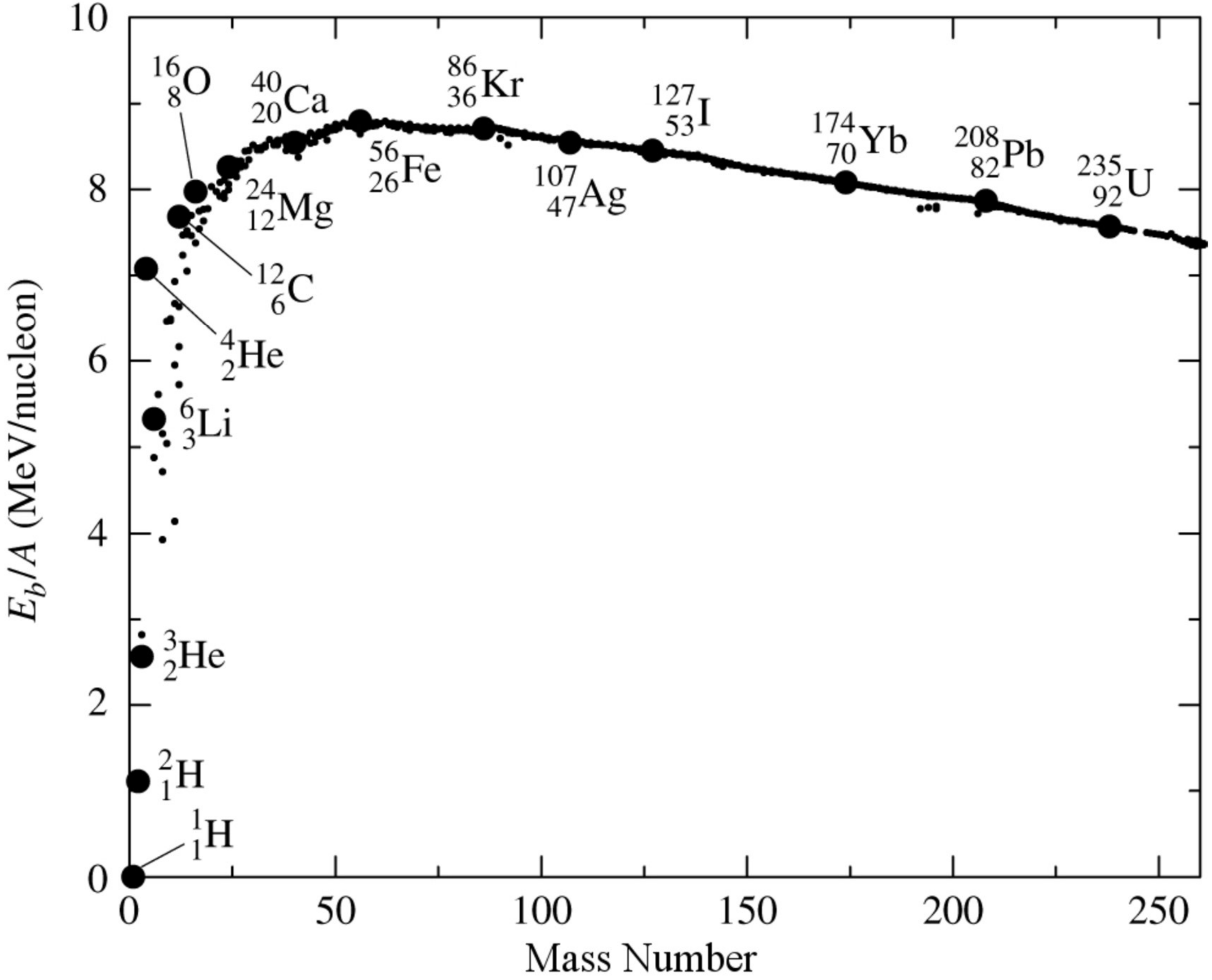


Symmetries (the deformed harmonic oscillator)





Nuclear Binding Energy



Theory: around 9000 nuclei

On Earth: 92 elements, 83 stable; 263 stable isotops

The heaviest elements in laboratory: Z=116, 118

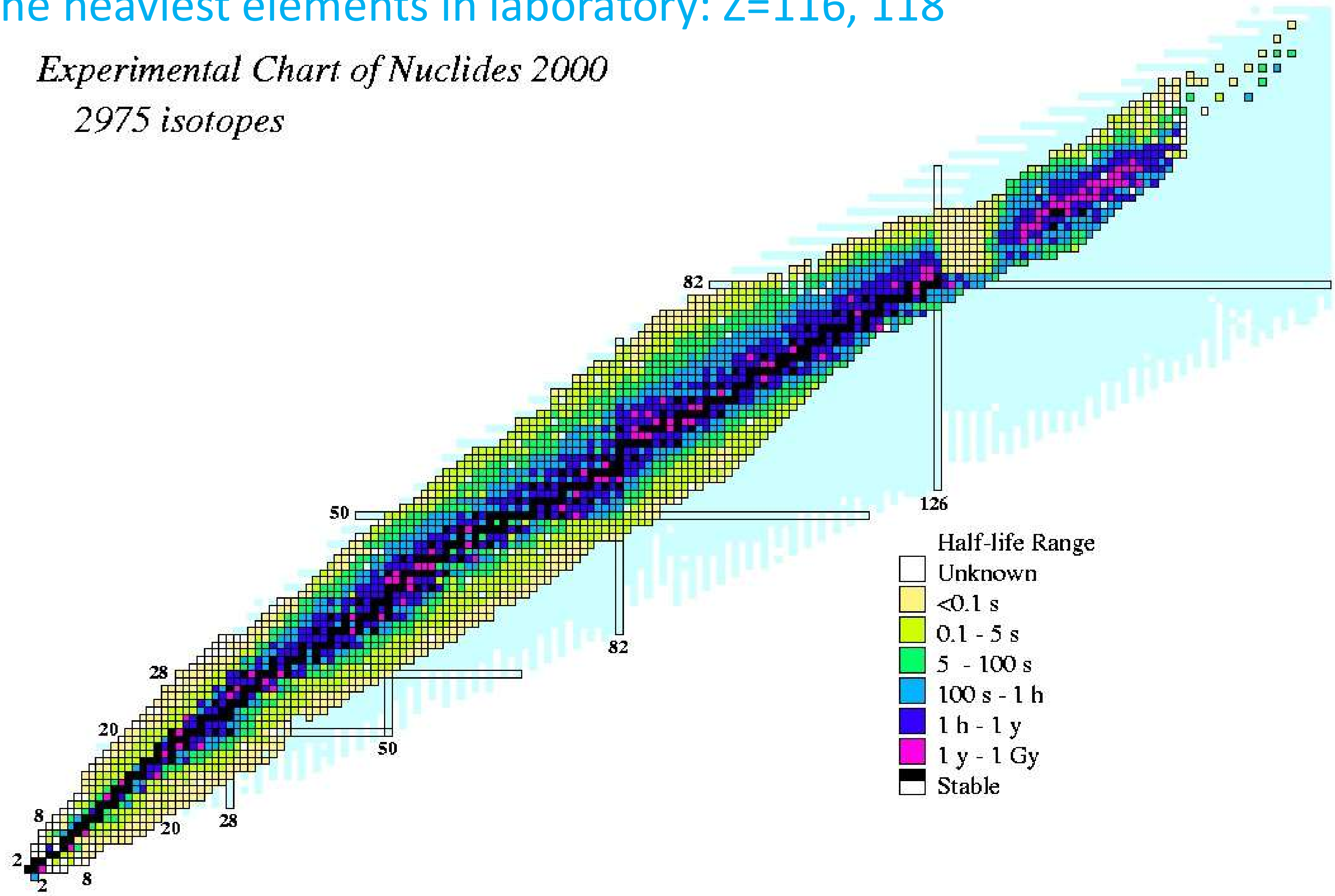
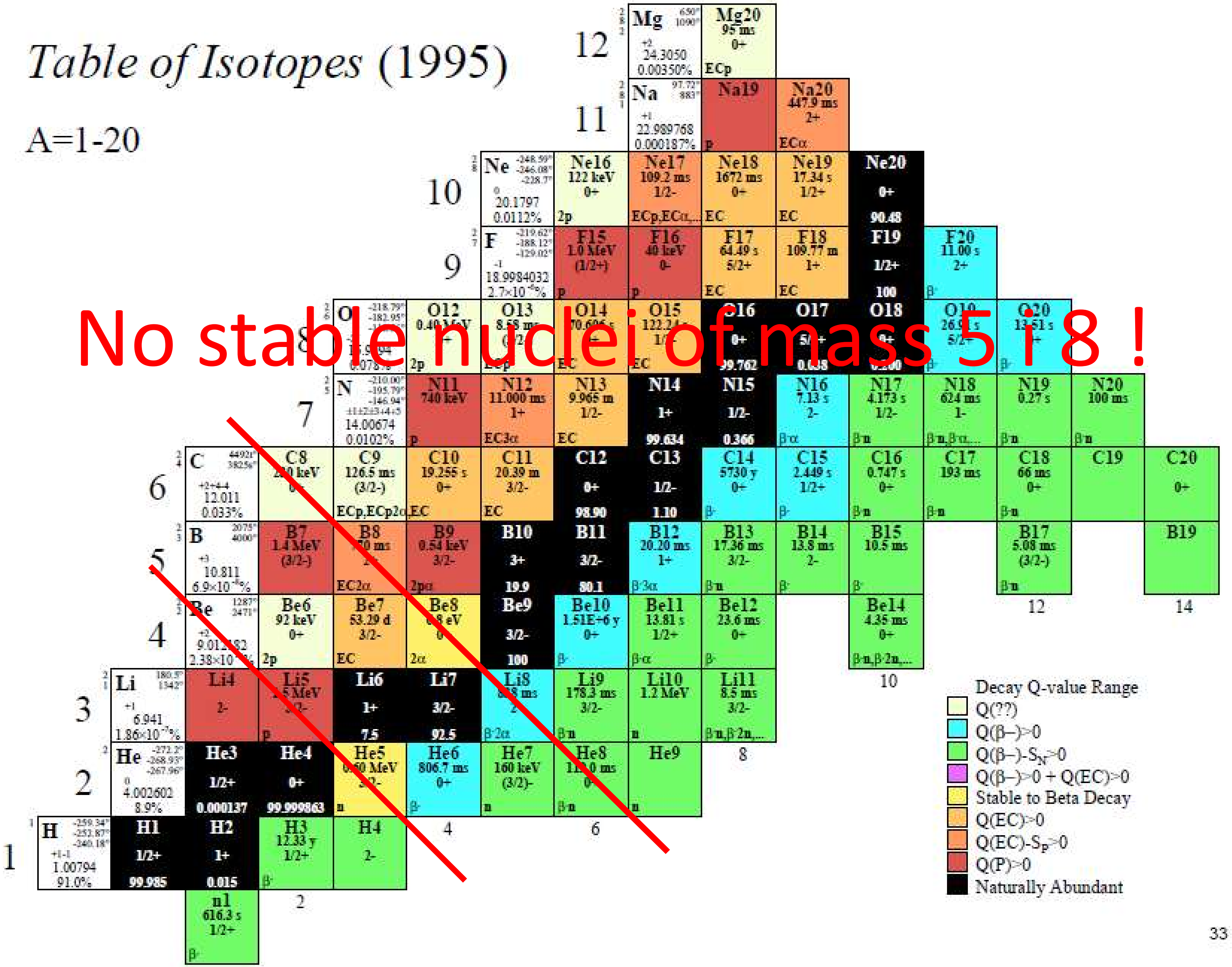


Table of Isotopes (1995)

A=1-20



No stable nuclei of mass 5 i 8 !

Type of processes

Transfer (strong interaction)

$$^{15}\mathrm{N}(p,\alpha)^{12}\mathrm{C}, \qquad \sigma \simeq 0.5\ \mathrm{b\ at}\ E_p = 2.0\ \mathrm{MeV}$$

Capture (electromagnetic interaction)

$$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}, \qquad \sigma \simeq 10^{-6}\ \mathrm{b\ at}\ E_p = 2.0\ \mathrm{MeV}$$

Weak (weak interaction)

$$p(p,e^{+}\nu)d, \qquad \sigma \simeq 10^{-20}\ \mathrm{b\ at}\ E_p = 2.0\ \mathrm{MeV}$$

$$\mathrm{b} = 100\ \mathrm{fm}^2 = 10^{-24}\ \mathrm{cm}^2$$

Cross section determination

The calculation of the cross section requires the determination of the wave function for the system projectile (a) and target (A) for a particular value of energy E. This requires solutions of the Schrodinger equation for a potential

$$V(r) = V_{\text{nuclear}}(r) + V_{\text{coulomb}}(r) + V_{\text{centrifugal}}(r)$$

- Nuclear potential: complicated form with strong dependence on energy, E, angular momentum, J and parity, π (due to the internal structure of the target and projectile). It is of very short range: $R = 1.2(A_a^{1/3} + A_A^{1/3})$ fm.
- Coulomb potential (only for charged particles):

$$V(r) = \frac{Z_a Z_A e^2}{r}$$

- Centrifugal barrier:

$$V(r) = \frac{\hbar^2 l(l+1)}{2mr^2}$$

  cross section suppressed for high l values. Normally s-wave ($l = 0$) and p-wave ($l = 1$) dominate.

Cross section is mainly determined by long range behaviour of the potential

Cross section

The general form of the total cross section for the formation of a nucleus with $A_C = A_a + A_A$ and $Z_C = Z_a + Z_A$

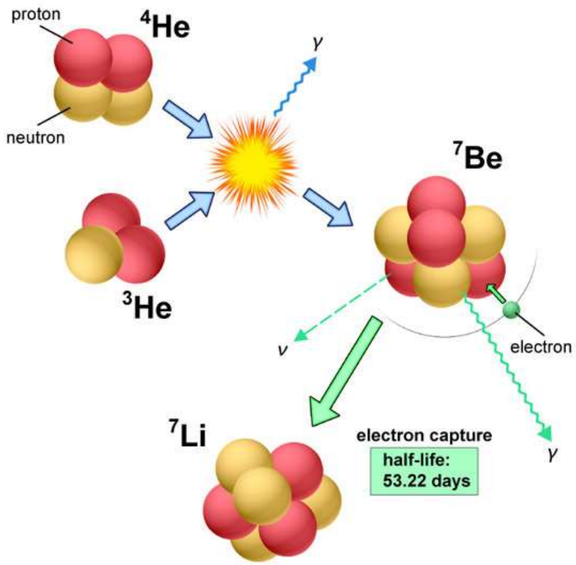
$$a + A \rightarrow C \rightarrow B + b$$

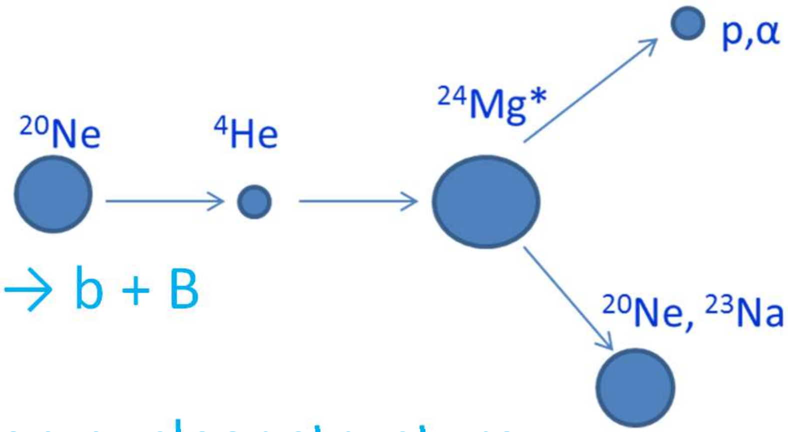
$$\sigma(E) = \pi\lambdabar^2 \sum_l (2l+1)T_l, \quad \lambdabar = \frac{\hbar}{mv} = \frac{\hbar}{\sqrt{2mE}}$$

T_l transmission coefficient through the potential barrier.

The problem reduces to a calculation of the tunneling probability through a barrier.

Nuclear reactions



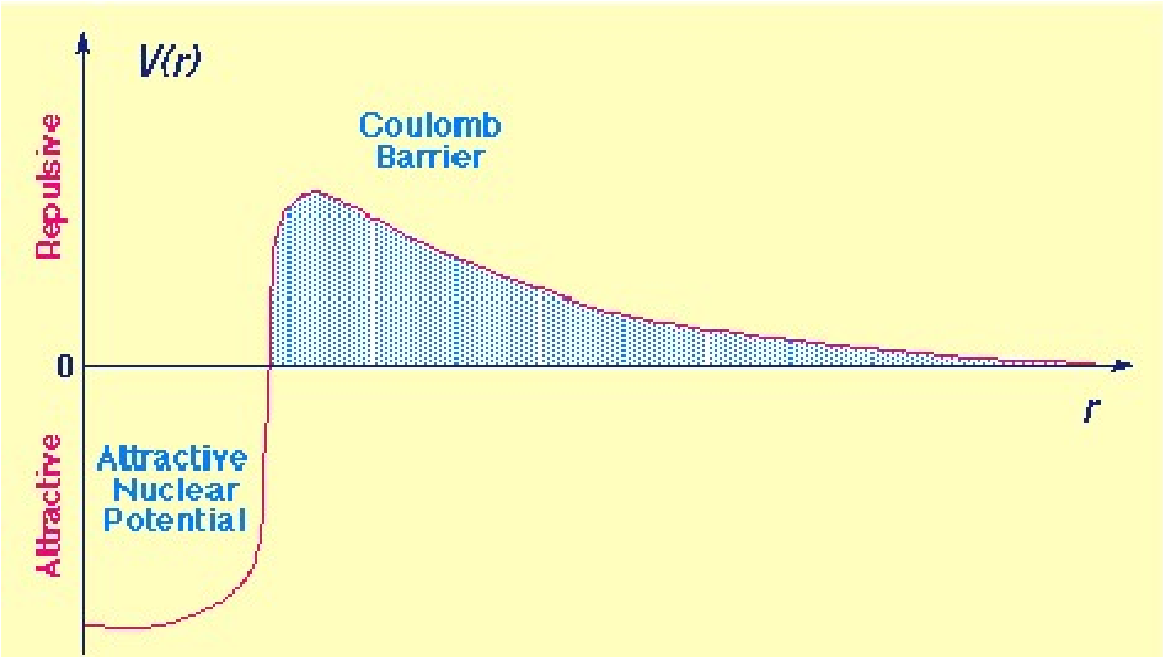


$A + a \rightarrow b + B$

Link between nuclear structure and reactions: reaction dynamics strongly depends on structure of colliding nuclei, especially at low energies (astrophysical environment)

- Reaction Q-value: $Q = [(m_a + m_A) - (m_b + m_B)] * c^2$
- Total reaction energy: beam energy + Q
- Beam energy defines type of dominant reaction mechanism for particular projectile - target combination

- Nuclear reactions: processes between positively charged nuclei: nuclear interaction starts when nuclei are close enough that nuclear force has an effect (10^{-15} m)
- Nuclei have to overcome Coulomb barrier (assuming s-wave dominates)



$$V_c = \frac{Z_a Z_A e^2}{d}$$

$$V_c\ (\mathrm{MeV}) = 1.44\ (\mathrm{MeV\ \ fm}) \frac{Z_a Z_A}{d\ (\mathrm{fm})}$$

Coulomb barrier height:

p+p ⇨ $V_c \approx 600$ keV

p+^{12}C ⇨ $V_c \approx 2.8$ MeV

α+α ⇨ $V_c \approx 1.5$ MeV

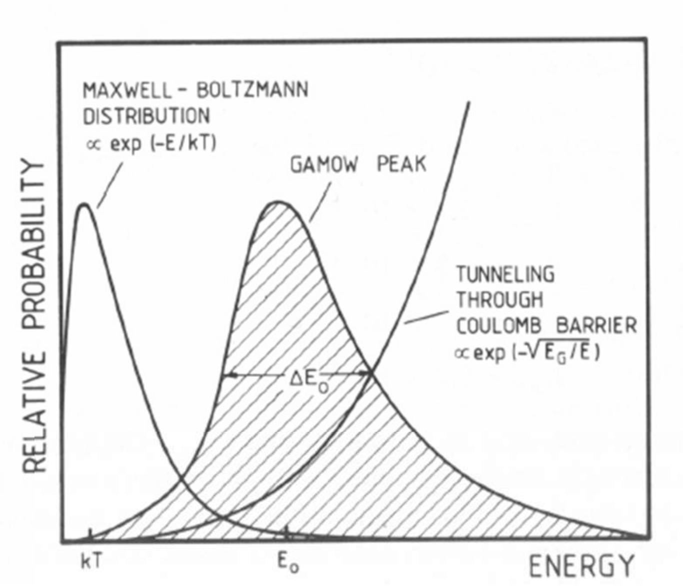
^{16}O+^{16}O ⇨ $V_c \approx 15.0$ MeV

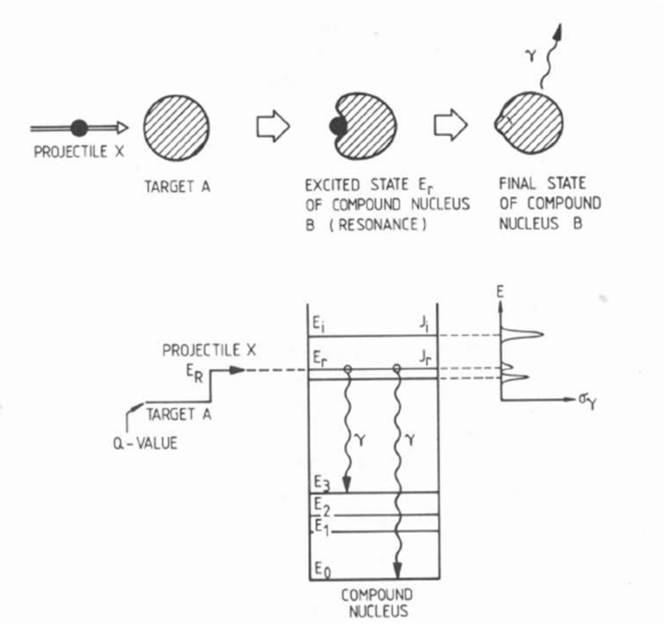
Sun center:

T ~ 15×10^6 K ($T_6 = 15$)

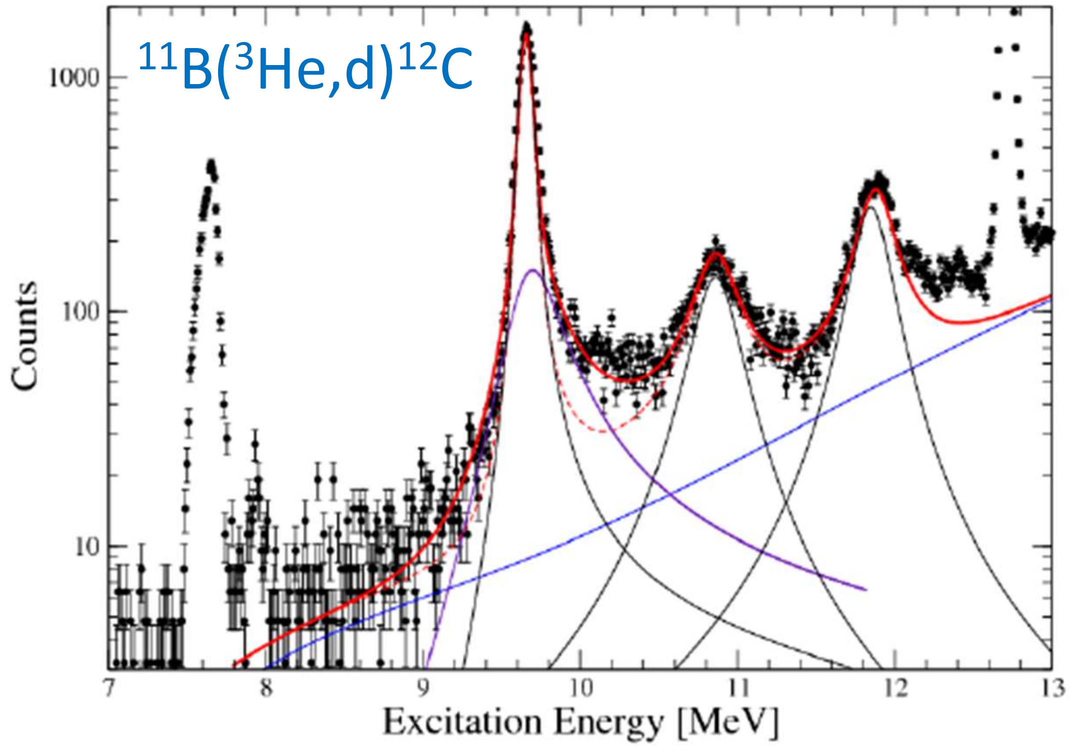
reaction	Coulomb barrier (MeV)	E_0 (keV)	Reaction rate (Gamow peak area)
p + p	0.55	5.9	7.0×10^{-6}
α + ^{12}C	3.43	56	5.9×10^{-56}
^{16}O + ^{16}O	14.07	237	2.5×10^{-237}

Gamow window



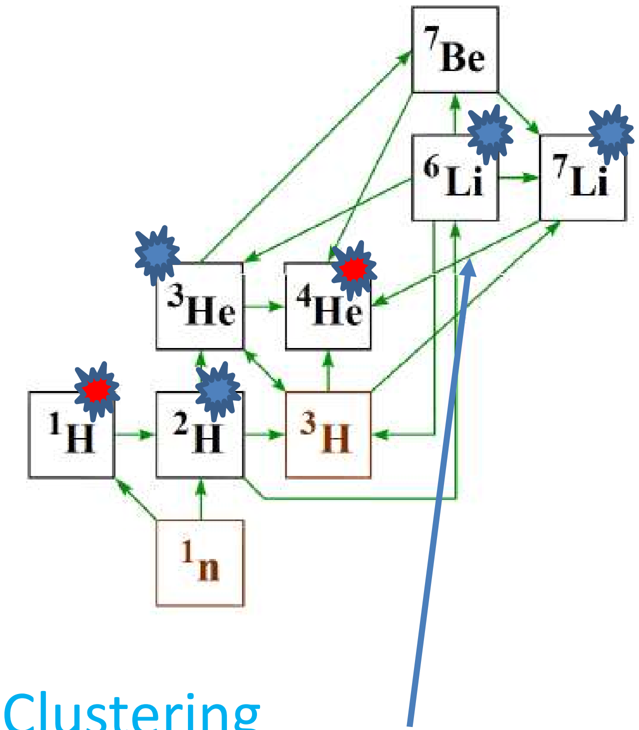


Reaction probability (cross section) can change a few order of magnitudes with very small beam energy change → RESONANCES



Genesis of elements

Big Bang Nucleosynthesis



Clustering
Non-resonant processes

- Adequate density and temperature of matter from 3rd to 20th minute after the Big Bang
- $T \approx 10^{10}$ K → $kT \approx 2$ MeV
- Mass abundance:
  - hydrogen: $^{1}H \approx 75\%$, helium: $^{4}He \approx 25\%$
  - deuteron ^{2}H: cca 2.5×10^{-5}
  - ^{3}He: cca 1×10^{-5}
  - ^{7}Li: cca 1.5×10^{-10}
  - ^{6}Li cca 5×10^{-12}
- Today observed deuterons are primordial
- ^{3}He is generated in starts
- Lithium problem

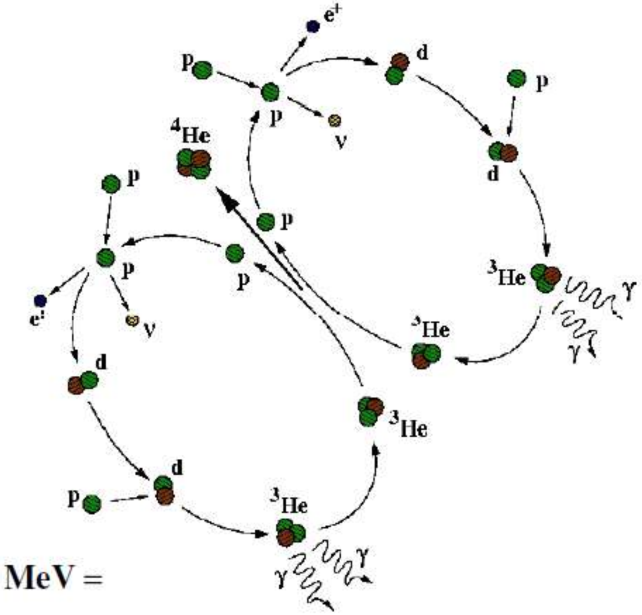
Nucleosynthesis in stars

- Stars: mixture of p & ^4He + e^-, capture reactions of p & ^4He
- No stable nuclei of mass 5 and 8 !
- Mass of star → temperature – reaction energy → upper limit of mass of produced nuclei
- The first step is hydrogen burning – all stars
- Primordial massive stars
- Sun generate energy through p – p cycle
- Sun $T \approx 15 \times 10^6$ K → $kT \approx 1$ keV
- Sun: star of 2nd or 3rd generation, contains also heavy elements
- Sun temperature is too low for reactions on nuclei $A > 8$

	Q / MeV
$p + p \rightarrow d + e^{+} + \nu$	1.442
$d + p \rightarrow {}^{3}\text{He} + \gamma$	5.493
${}^{3}\text{He} + {}^{3}\text{He} \rightarrow {}^{4}\text{He} + 2p$	12.859

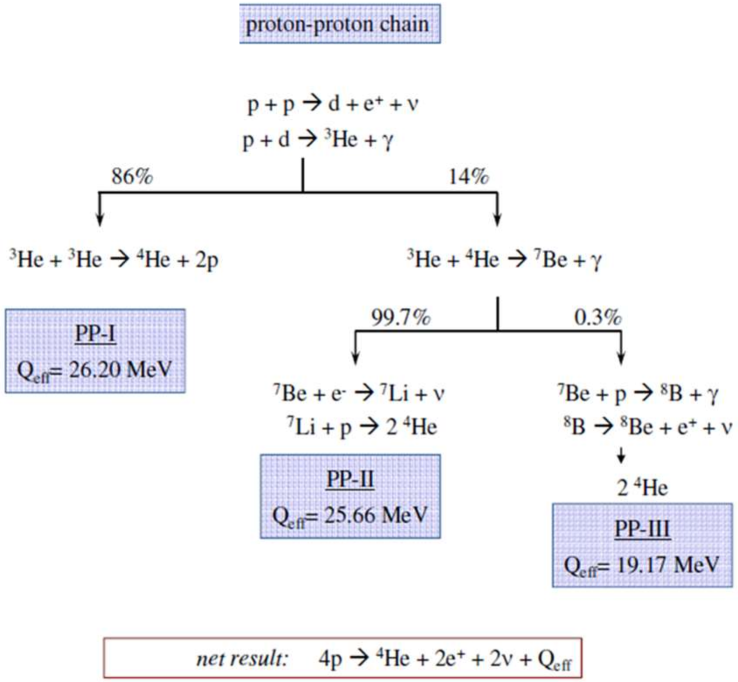
- Total Q

$2\times1.442+2\times5.493$
$+12.859-2\times0.26\approx$
≈ 26.2 MeV



$$Q = (4m_p - m_\alpha)\cdot c^2 + 2m_e - 2\cdot 0.26\,\textbf{MeV} =$$
$$= (4\cdot 1.00728 - 4.00151)\cdot 931.5\,\textbf{MeV} + 2\cdot 511\,\textbf{keV} - 0.52\,\textbf{MeV} =$$
$$\approx 26.2\,\textbf{MeV}$$

Non-resonant processes

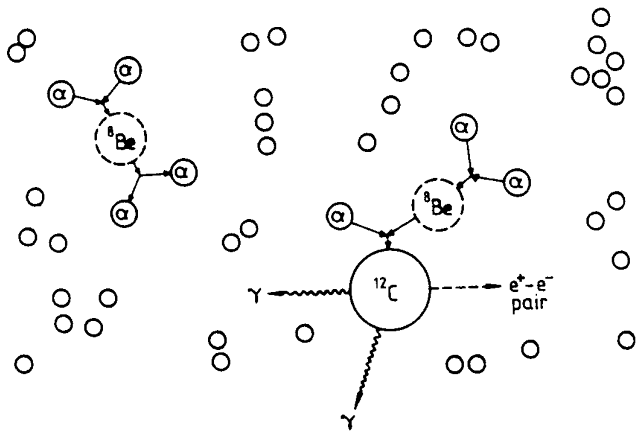


Helium burning – 3α reaction

- Which process produce nuclei A > 8 ?
- Answer: $\alpha + \alpha + \alpha \rightarrow {}^{12}C$ CLUSTERING !!
- 2 step process:
    1. $\alpha + \alpha \leftrightarrow {}^{8}Be(gs)$ $Q = -92.1$ keV, $\tau \approx 10^{-16}$ s
    2. ${}^{8}Be+\alpha \leftrightarrow {}^{12}C^{*}$(Hoyle state) $\tau \approx 10^{-16}$ s

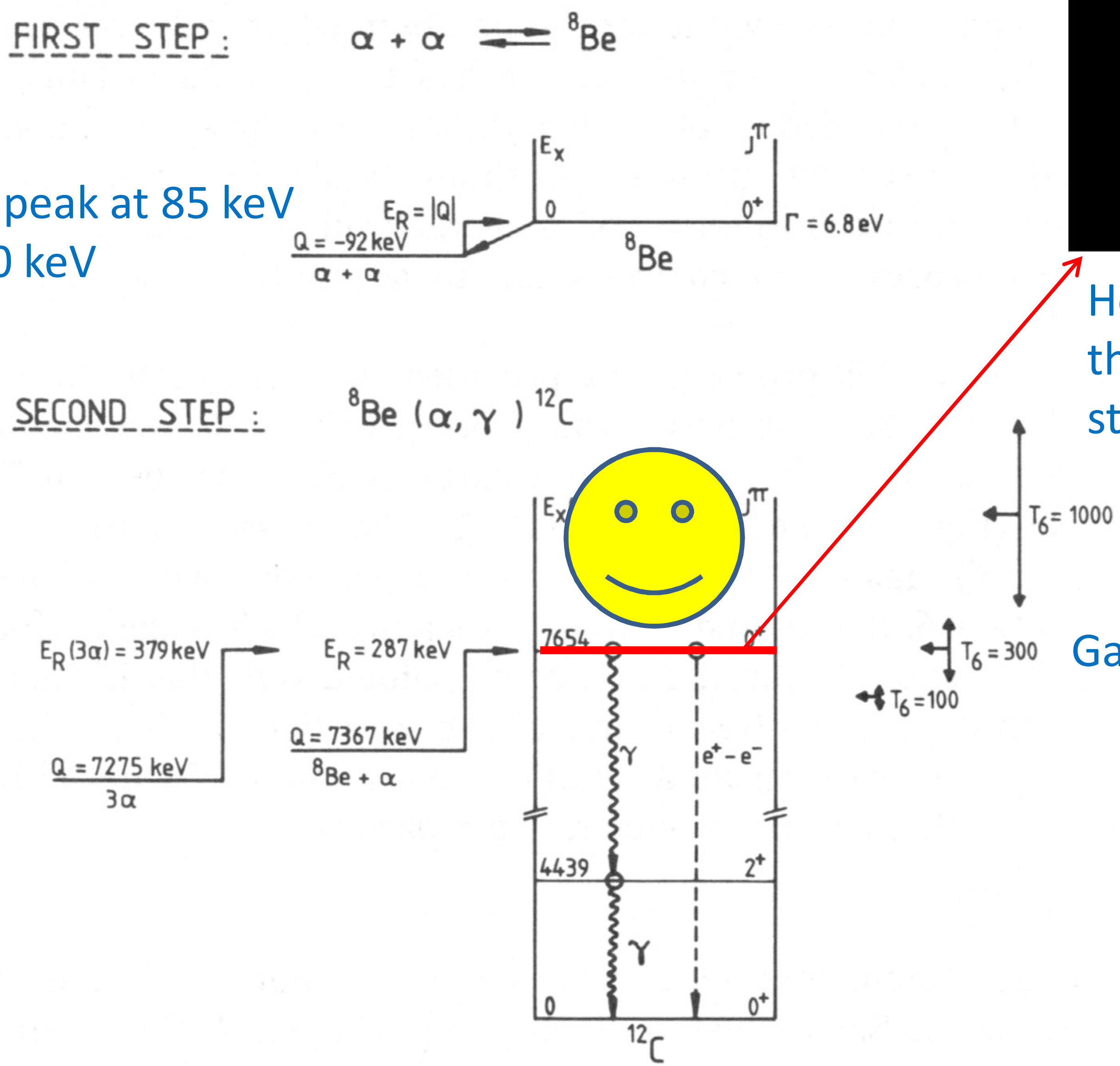
    2γ or $e^{+}e^{-}$ pair production$\rightarrow {}^{12}C$(g.s.) P(rad.dec.)$\approx 4\times10^{-4}$

Hoyle (1954): necessary condition is resonance in ${}^{12}C$ at certain energy and with specific characteristics: $J^{\pi}=0^{+}$ state at $E_x \approx$ 7.7 MeV; such state increases production rate for factor 10^{8} !

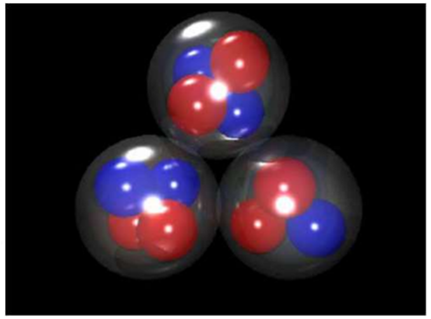


Red giant conditions: equilibrium ${}^{8}Be/{}^{4}He = 10^{-10}$

Gamow peak at 85 keV
width 60 keV



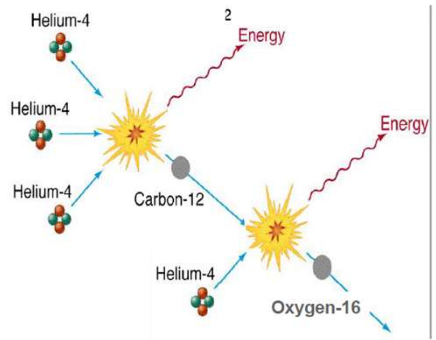
Gamow peak



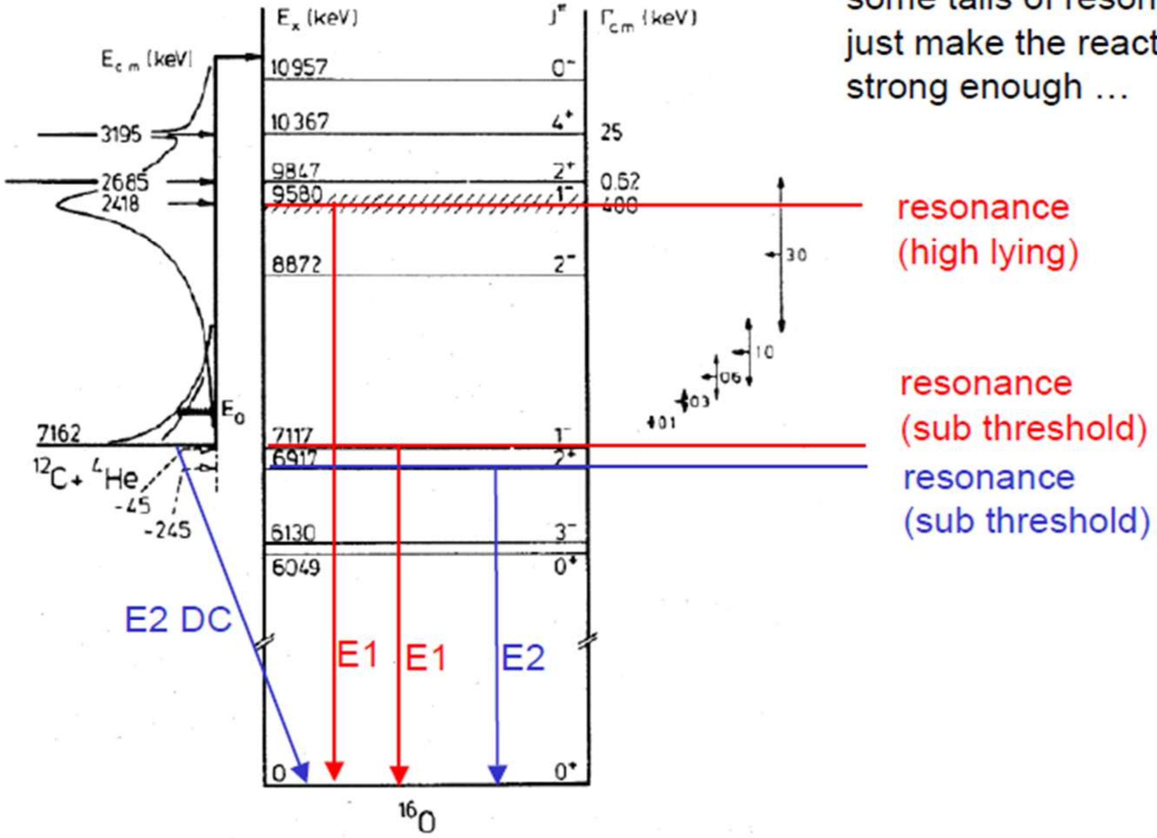
Hoyle state posses the ^{8}Be+α cluster structure

The first application of Anthropic principle

$^{12}C(\alpha,\gamma)^{16}O$



some tails of resonances just make the reaction strong enough …

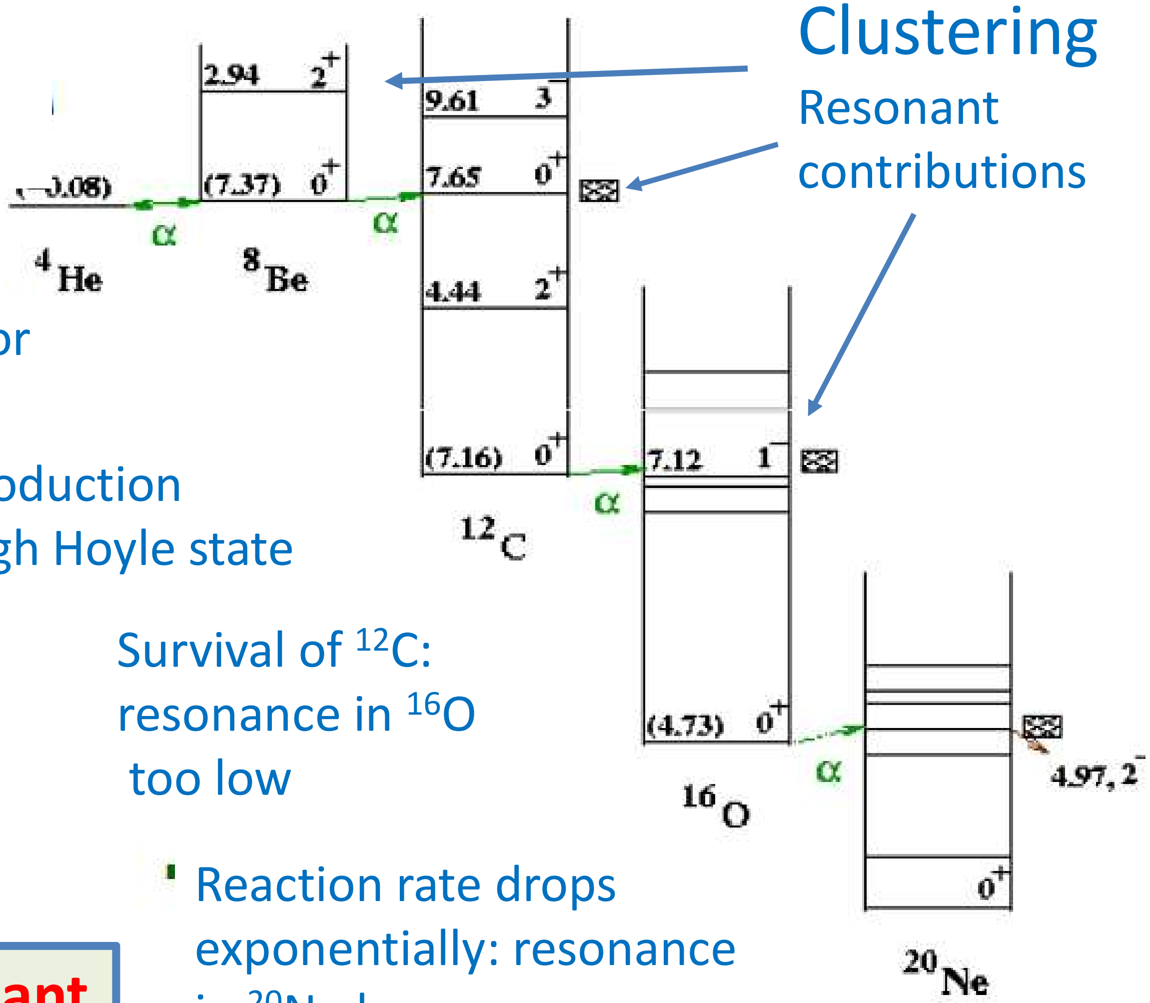


complications:

- very low cross section makes direct measurement impossible
- subthreshold resonances cannot be measured at resonance energy
- Interference between the E1 and the E2 components

Stages of helium burning

Nucleosynthesis continue by further capture of α-particles



Clustering

Resonant contributions

Enough ^{8}Be for the next step

^{12}C production through Hoyle state

Survival of ^{12}C: resonance in ^{16}O too low

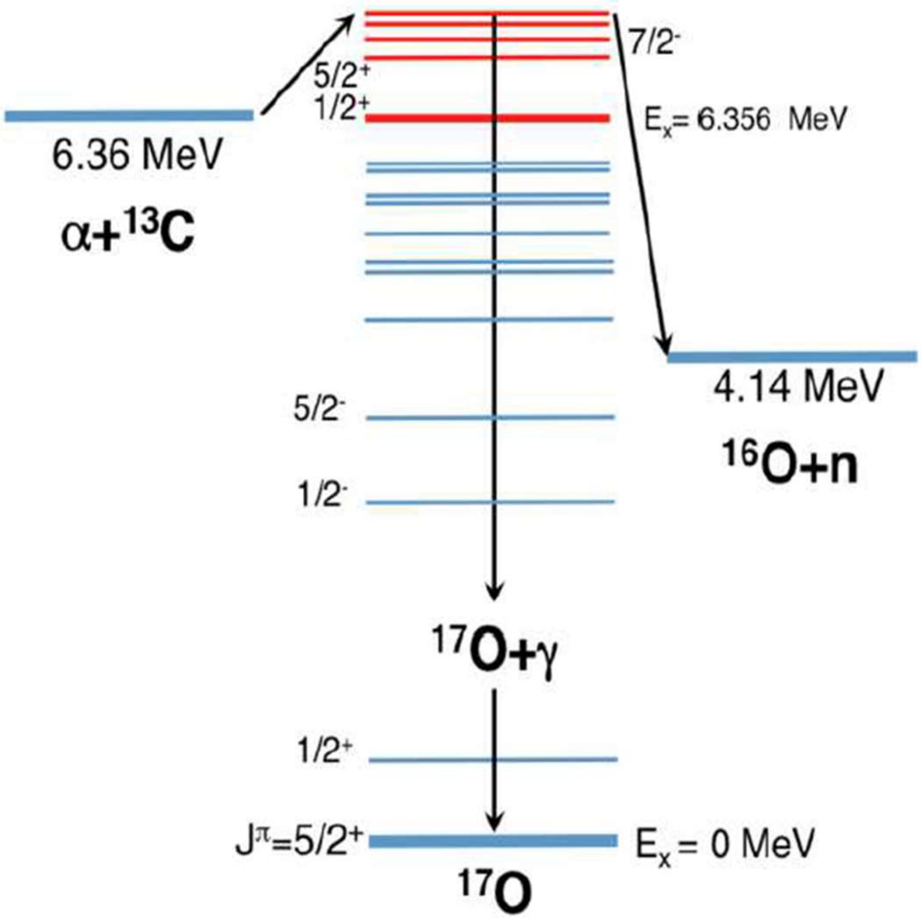
- Reaction rate drops exponentially: resonance in ^{20}Ne has wrong characteristics

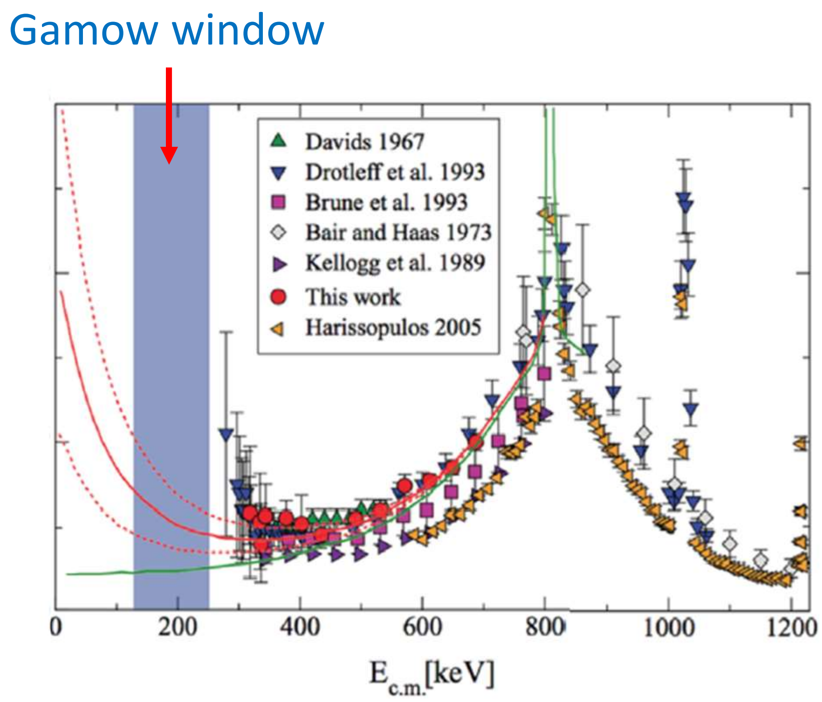
Result: a lot of carbon & oxygen C/O≈0.6

O 3rd, C 4th most abundant element in the Universe

$^{13}C(\alpha,n)^{16}O$

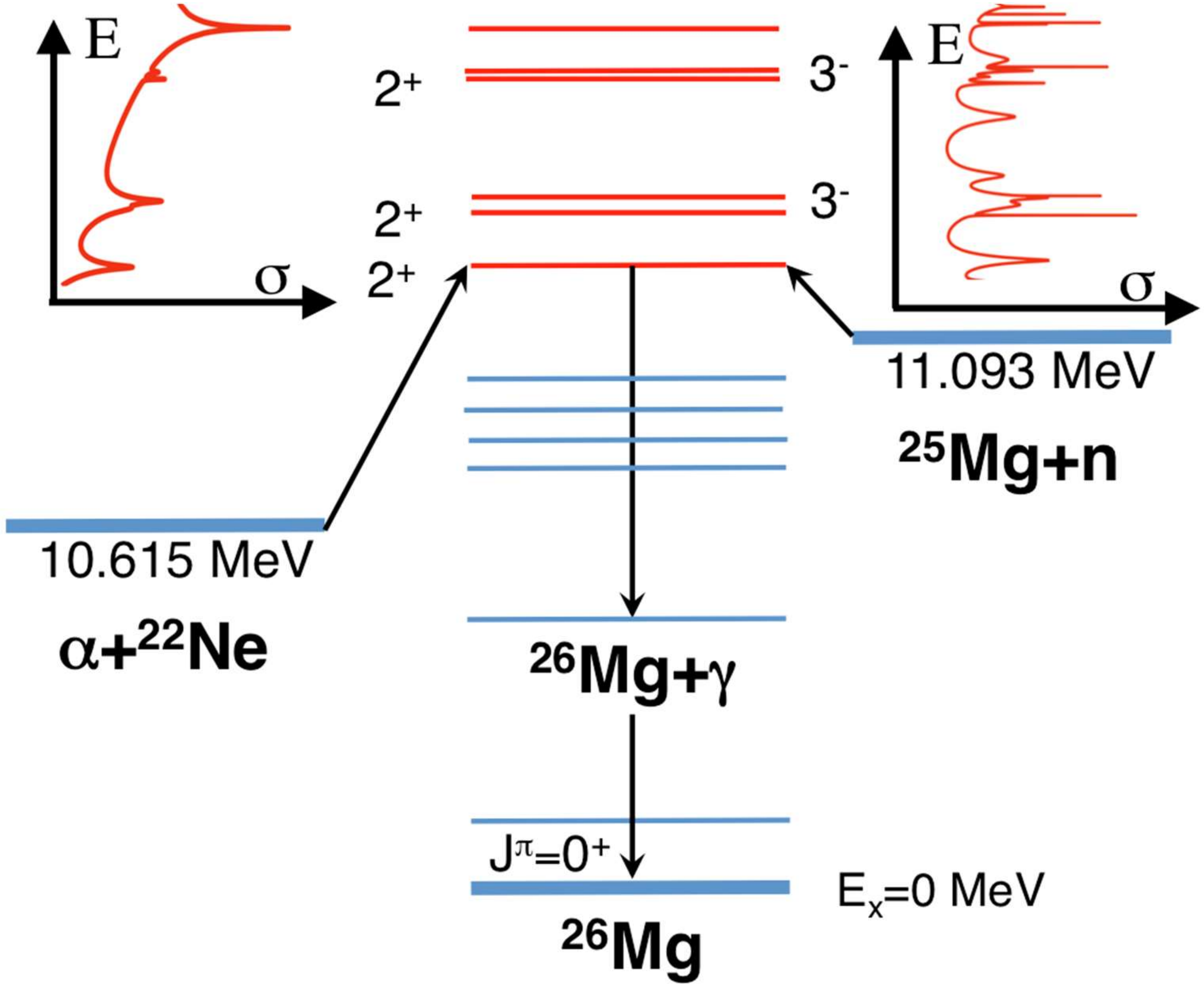
- main neutron source for the s-process in low mass AGB stars





$^{22}Ne(\alpha,n)^{25}Mg$

- main neutron source for the s-process in large mass AGB stars



$^{14}O(\alpha,p)^{17}F$

- breakout route from HCNO cycle

Information on $^{14}O(\alpha,p)^{17}F$ reaction rate from:

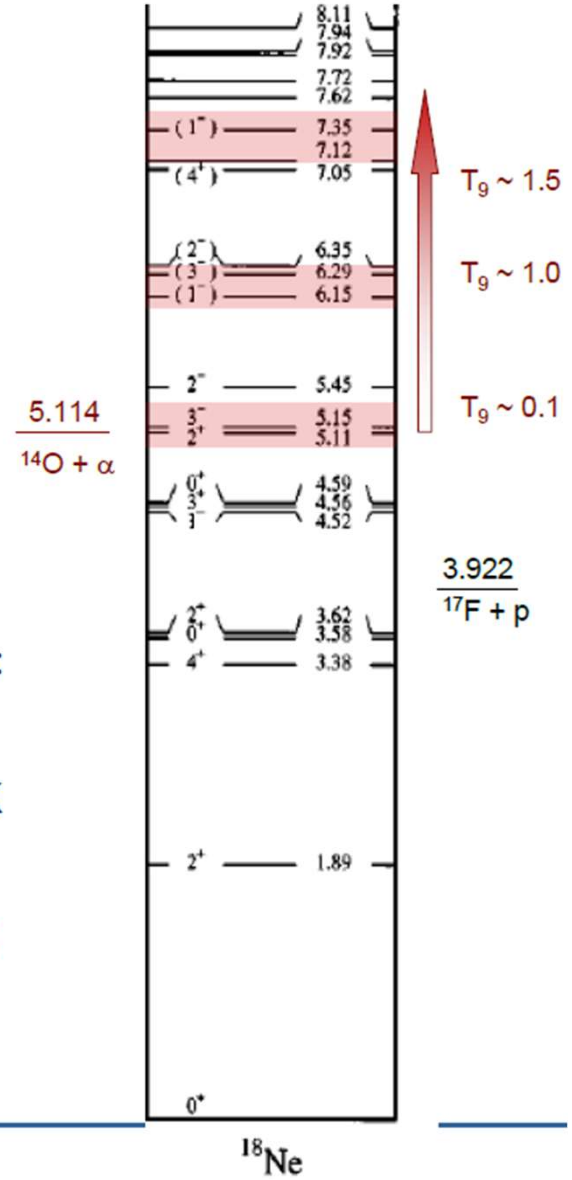
- level structure of ^{18}Ne
- theoretical calculations
- inverse reaction $^{17}F(p,\alpha)^{14}O$
- some direct data

main, expected contributions to reaction rate from:

resonance at 6.15 MeV $J^{\pi} = 1^{-}$ — @ $T \leq 1.0 \times 10^{9}$ K

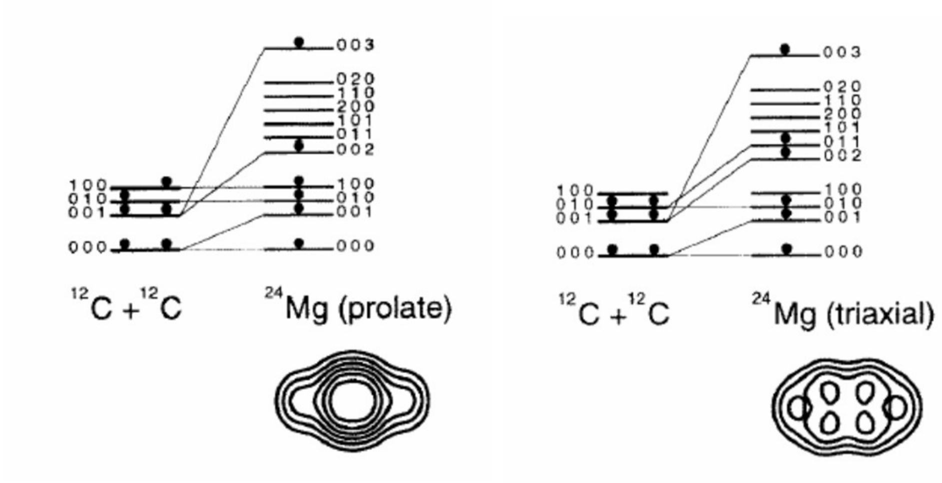
direct contribution with $l = 1$

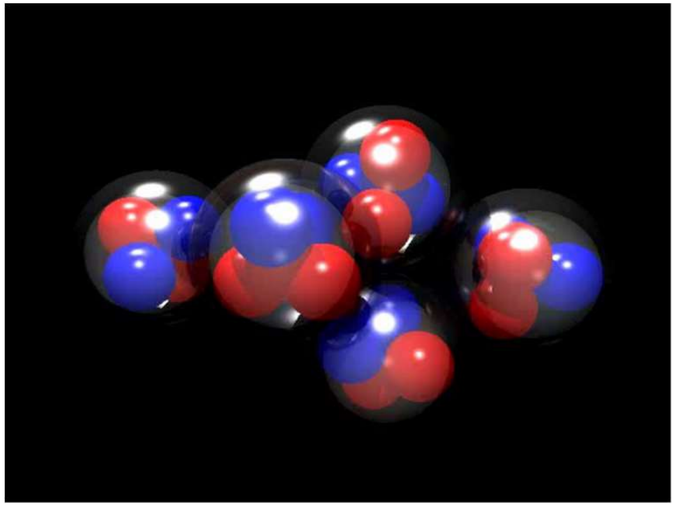
states at ~ 7 MeV — @ $T \geq 1.5 \times 10^{9}$ K



Carbon burning

Red super-giants with mass > 8 Sun mass, T=0.6 – 1 GK
Reaction sequence (Coulomb barrier): $^{12}C+^{12}C$, $^{12}C+^{16}O$, $^{16}O+^{16}O$
^{24}Mg is very special nucleus: $^{12}C+^{12}C$ structure



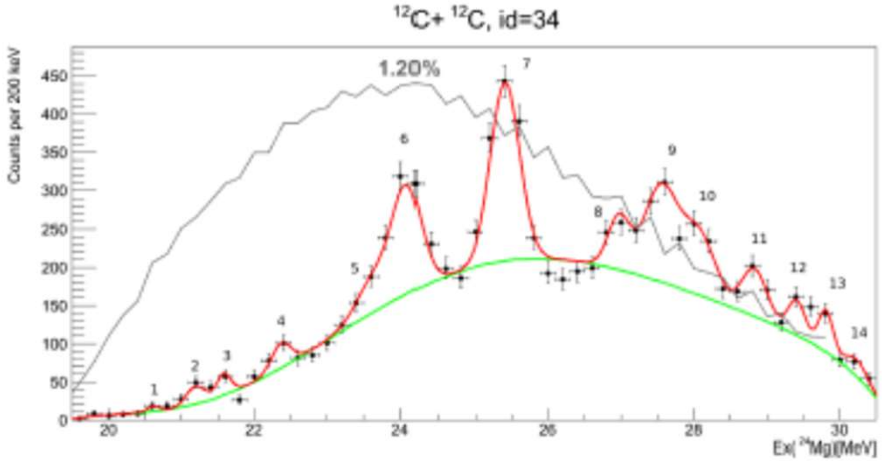


Very high excitation energies → de-excitation by emission of light nuclei
Evolution of very massive stars >15 M(Sun): neutron star or black hole ?
Trigger of explosive process of γ-burnst, supernovae type Ia & II

Is there $J^{\pi}=0^{+}$ resonance with $^{12}C+^{12}C$ structure in the Gamow window ?

Relevant reactions: $^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha$, Q=4.617 MeV

$^{12}C + ^{12}C \rightarrow ^{23}Na + p$, Q=2.239 MeV



20 MeV

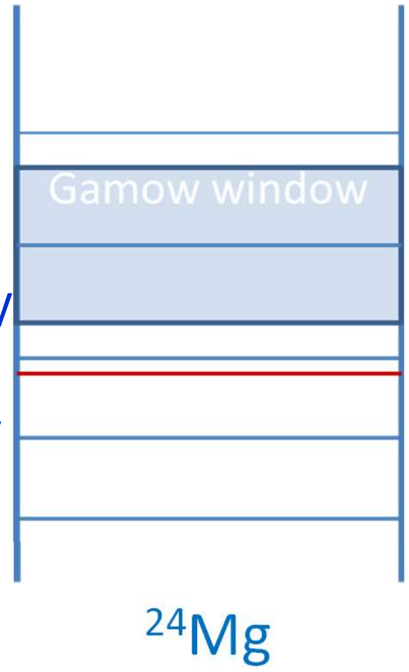
$E_{thr}(n+^{23}Ne)$ = 16.532 MeV

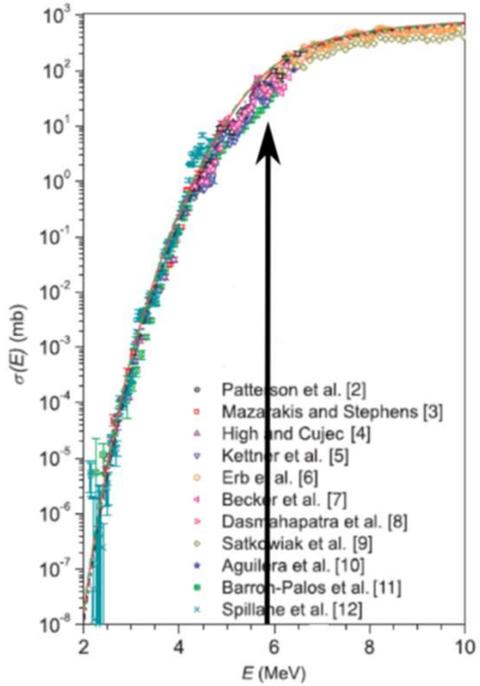
$E_{thr}(\alpha+\alpha+^{16}O)$ = 14.044 MeV

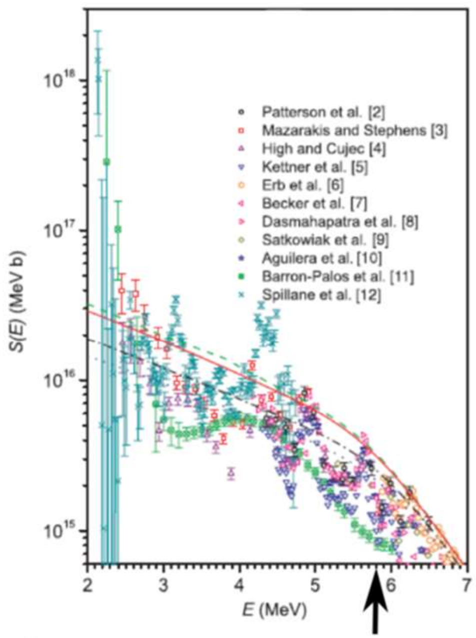
$E_{thr}(^{12}C+^{12}C)$ = 13.931 MeV

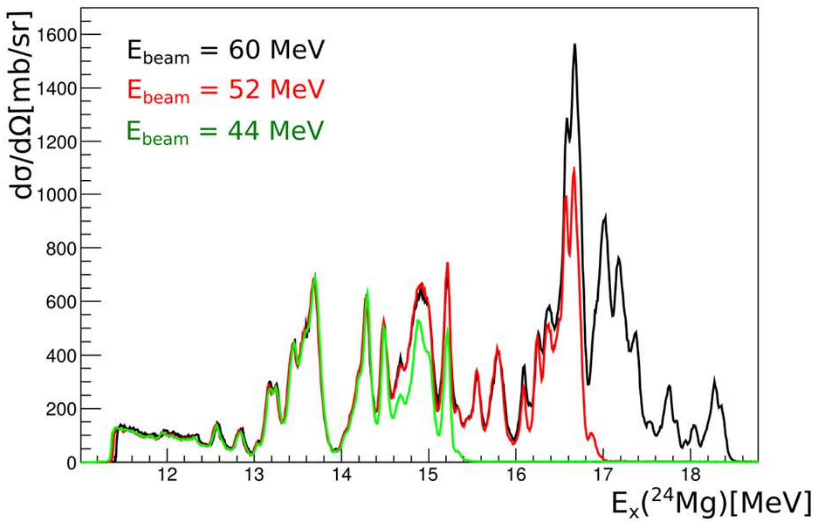
$E_{thr}(^{1}H+^{23}Na)$ = 11.692 MeV

$E_{thr}(\alpha+^{20}Ne)$ = 9.313 MeV









A. Tumino et al,
Nature 557 (2018) 687

THM : $^{12}C + ^{14}N \rightarrow d + ^{24}Mg^*$

$^{24}Mg^* \rightarrow \alpha + ^{20}Ne$

$^{24}Mg^* \rightarrow p + ^{23}Na$

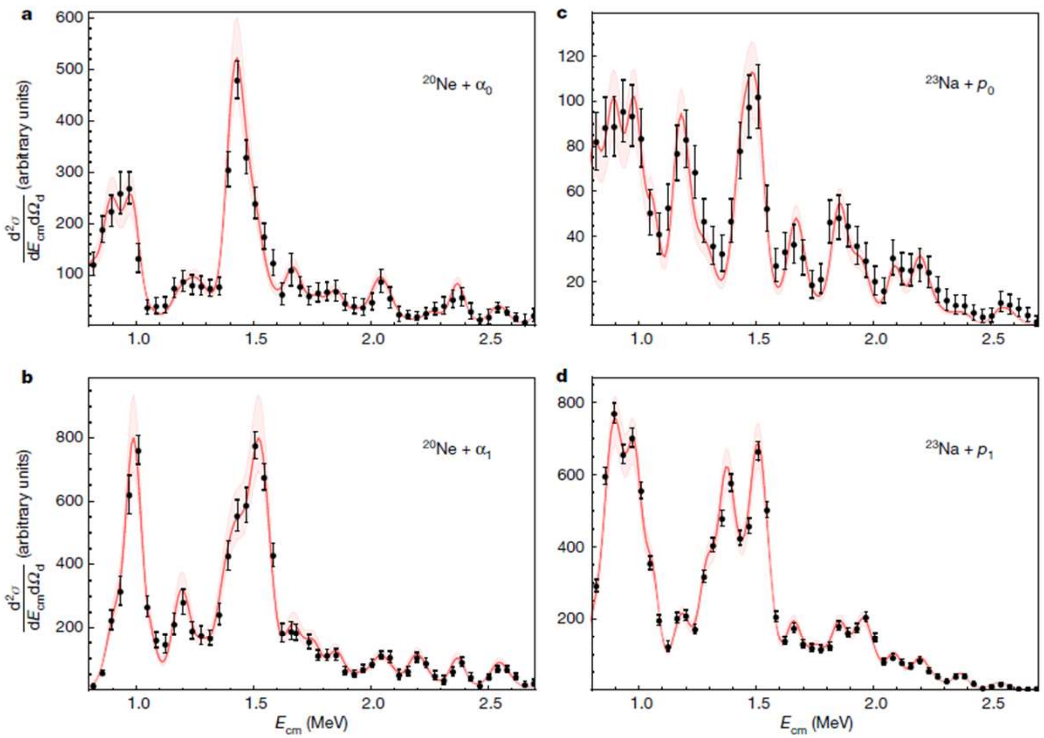
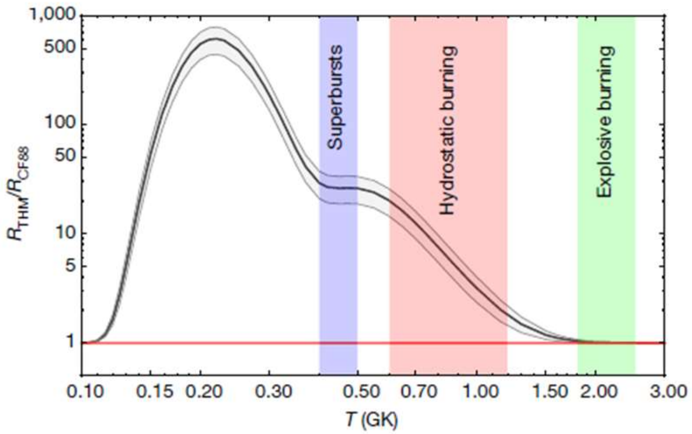


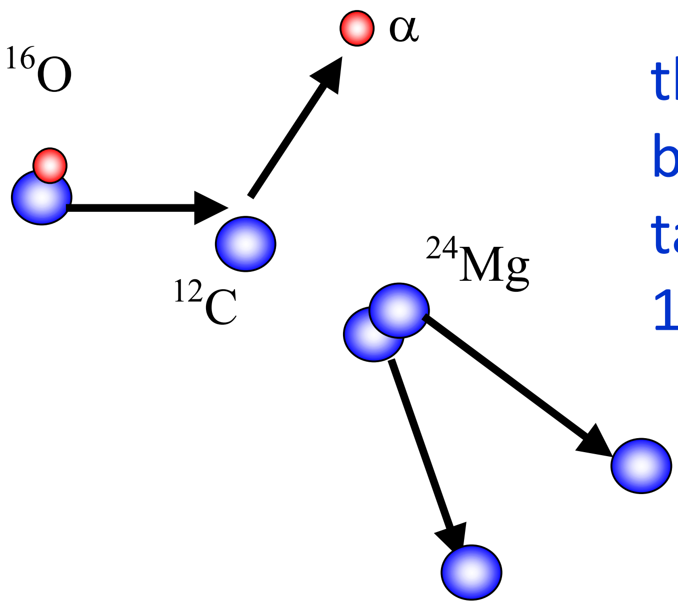
Fig. 1 | Excitation functions from THM experimental yields. The quasi-free cross-section for the four channels $^{20}Ne + \alpha_0$ (**a**), $^{20}Ne + \alpha_1$ (**b**), $^{23}Na + p_0$ (**c**) and $^{23}Na + p_1$ (**d**) is projected onto the E_{cm} variable (black dots). Error bars denote $\pm 1\sigma$ uncertainties and account for background subtraction (combined in quadrature). Red lines and light-red shading represent the results of the modified *R*-matrix fits and the related uncertainties, respectively.



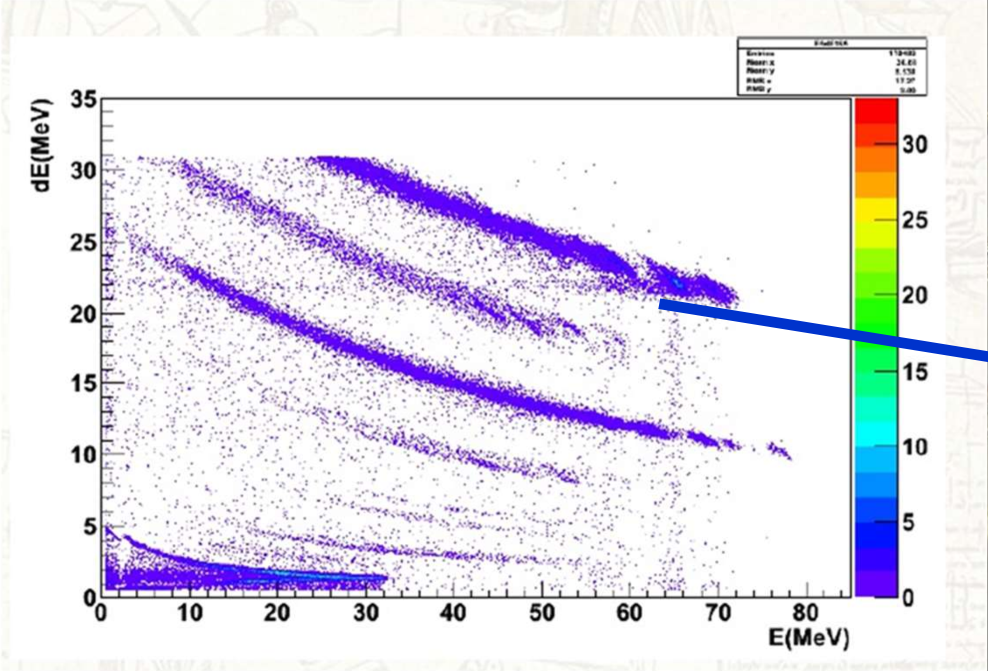
Experimental technique: Resonance Decay Spectroscopy

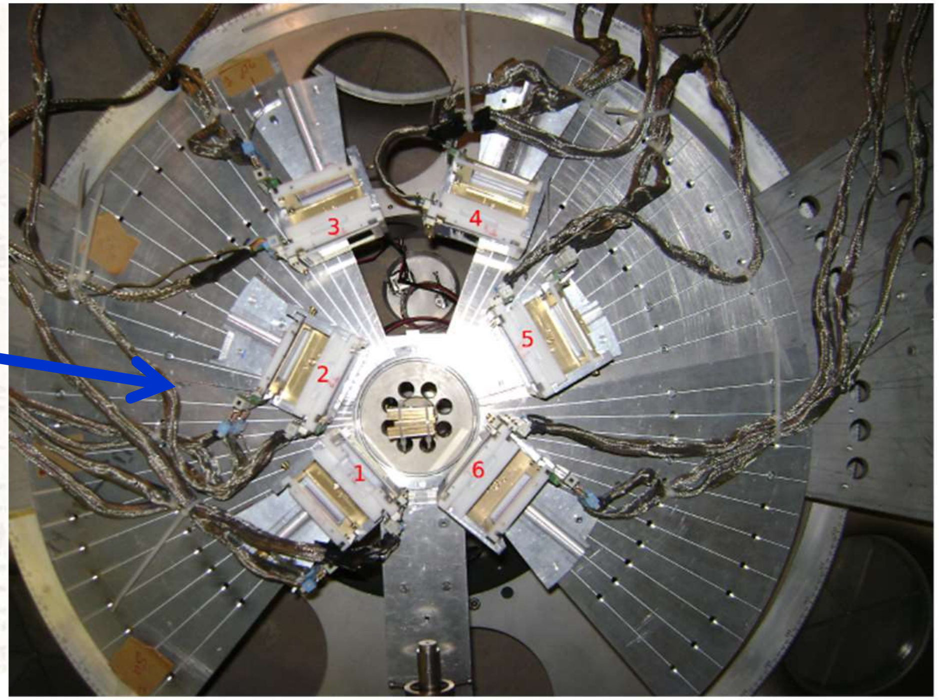
Coincident detection of 2 (or more) reaction products

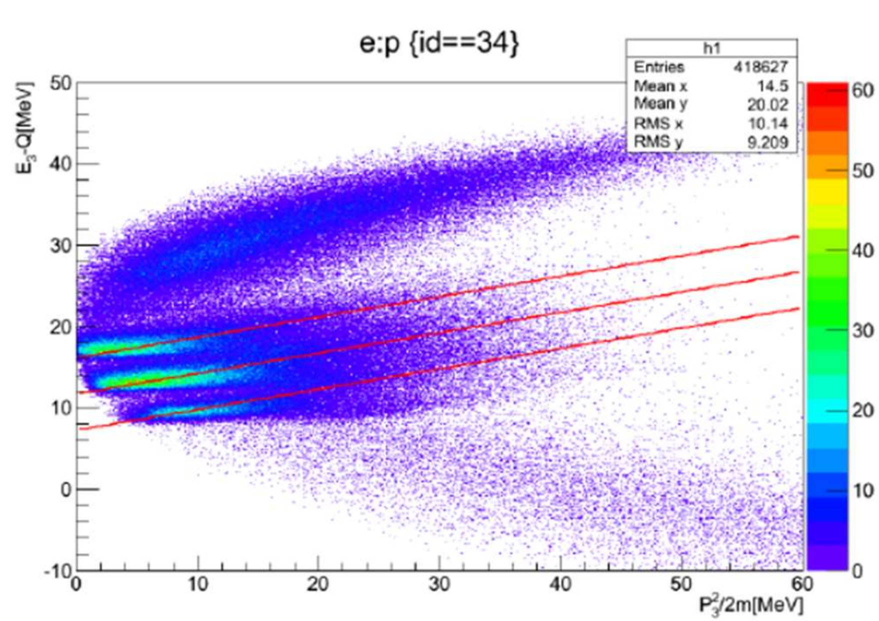
$^{12}C + ^{16}O \rightarrow ^{4}He + ^{12}C + ^{12}C$	Q=-7.16 MeV	$E_{thr}(^{24}Mg)$=13.93 MeV
$\rightarrow ^{4}He + ^{16}O + ^{8}Be$	Q=-7.37 MeV	$E_{thr}(^{24}Mg)$= 14.14 MeV
$\rightarrow ^{4}He + ^{20}Ne + ^{4}He$	Q=-2.54 MeV	$E_{thr}(^{24}Mg)$= 9.31 MeV
$\rightarrow ^{4}He + ^{23}Na + ^{1}H$	Q=-4.92 MeV	$E_{thr}(^{24}Mg)$= 11.69 MeV



the ^{16}O beam from the tandem accelerator
beam energy 94 MeV
target ^{12}C, thickness of 45 μg/cm^2
11 days of beam-time


dE(MeV)
E(MeV)


1
2
3
4
5
6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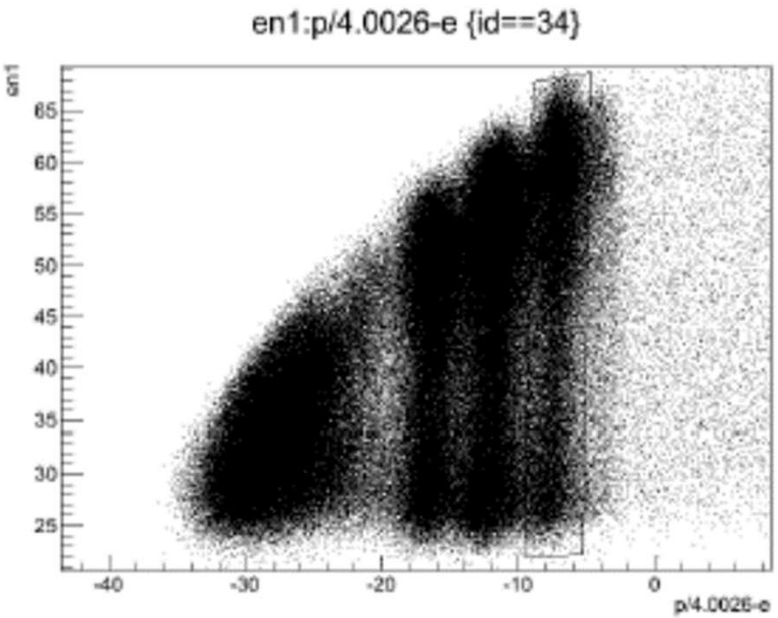
h1
Entries 418627
Mean x 14.5
Mean y 20.02
RMS x 10.14
RMS y 9.209
E3-Q[MeV]
P3²/2m[MeV]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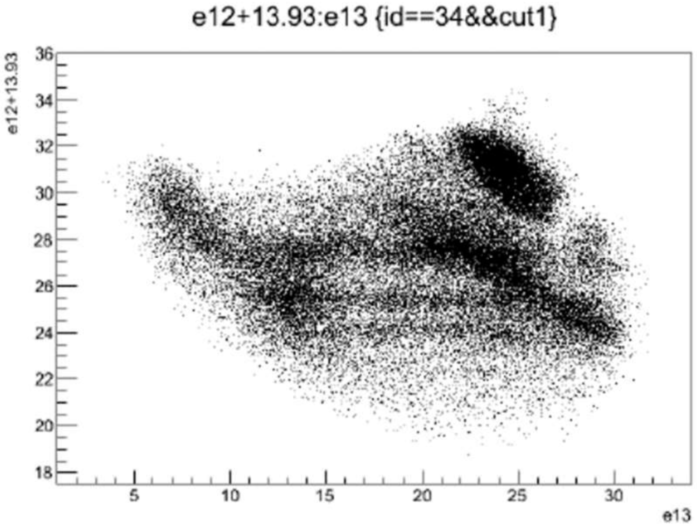
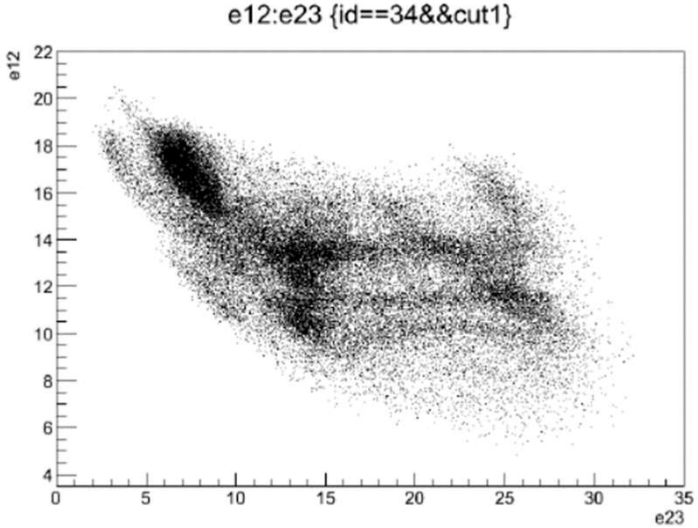
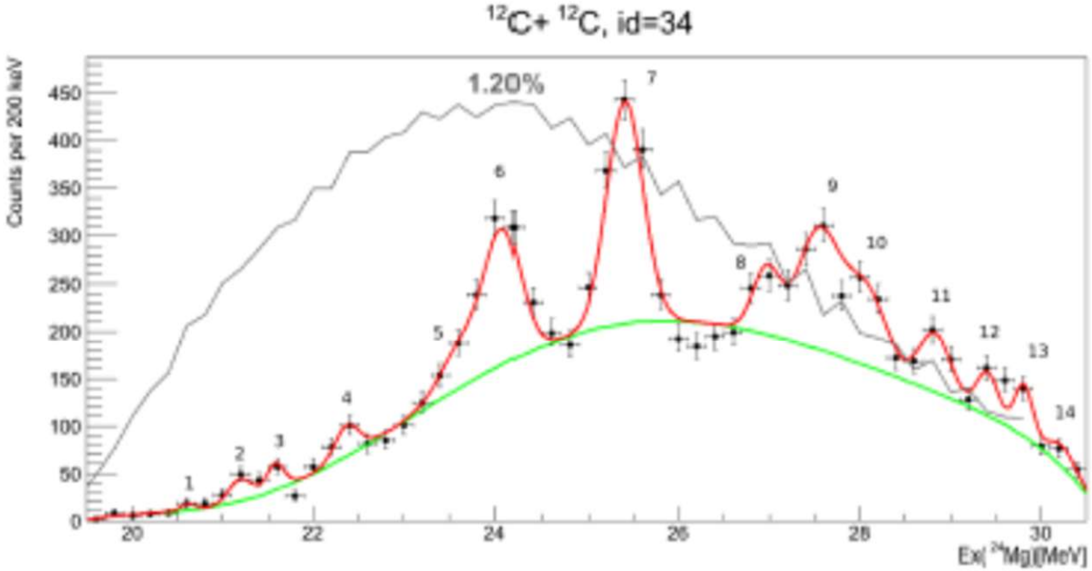
en1
p/4.0026-e



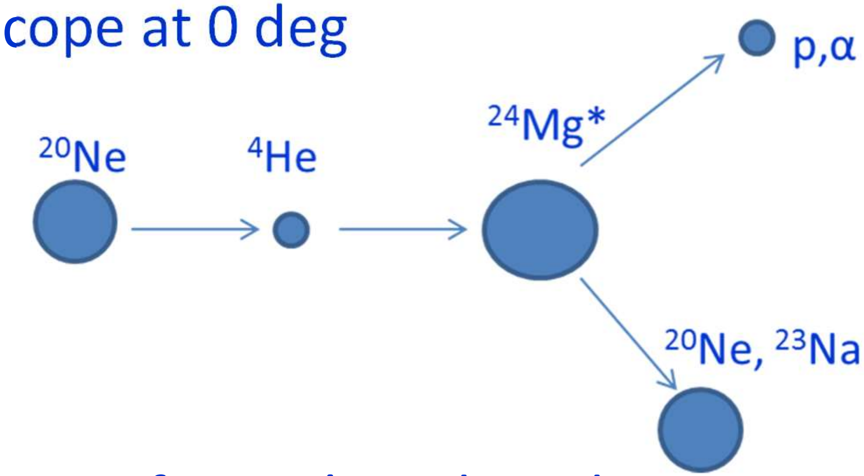




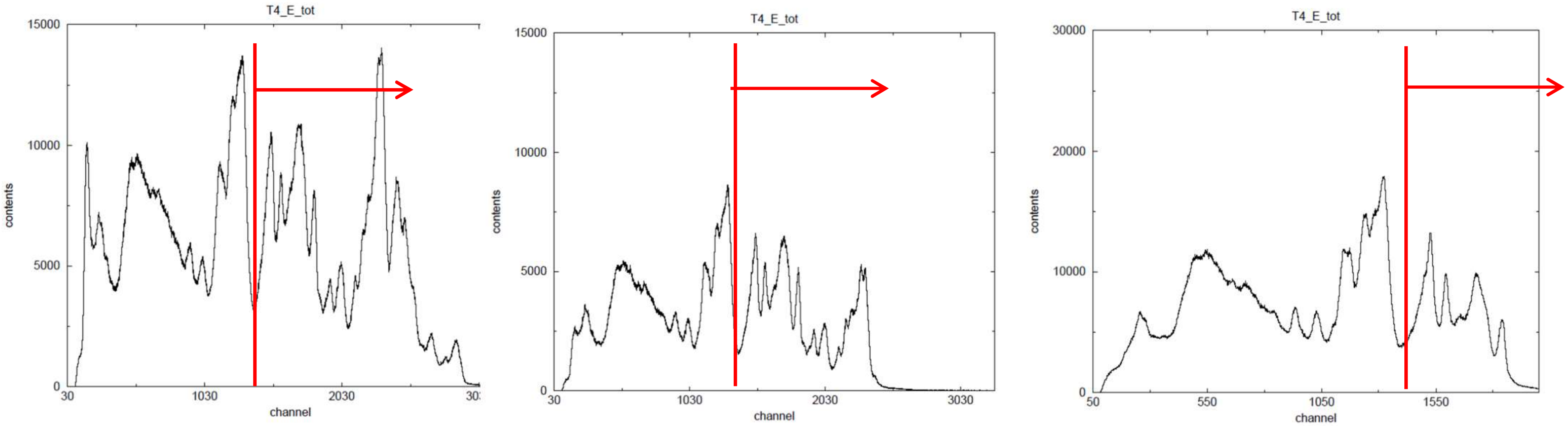
$E_x(^{24}Mg)$: 19.9, 20.9, 21.3, 21.7, 22.7, 23.8, 24.2, 25.6 (25.0+25.9 ?), 27.0, 27.6 (27.0+28.0 ?), 28.0, 28.8 (28.4+29.2 ?), 29.2, 30.4 MeV

Experimental technique: Gas Target Resonant Scattering

thick gas target exp: ΔE-E telescope at 0 deg

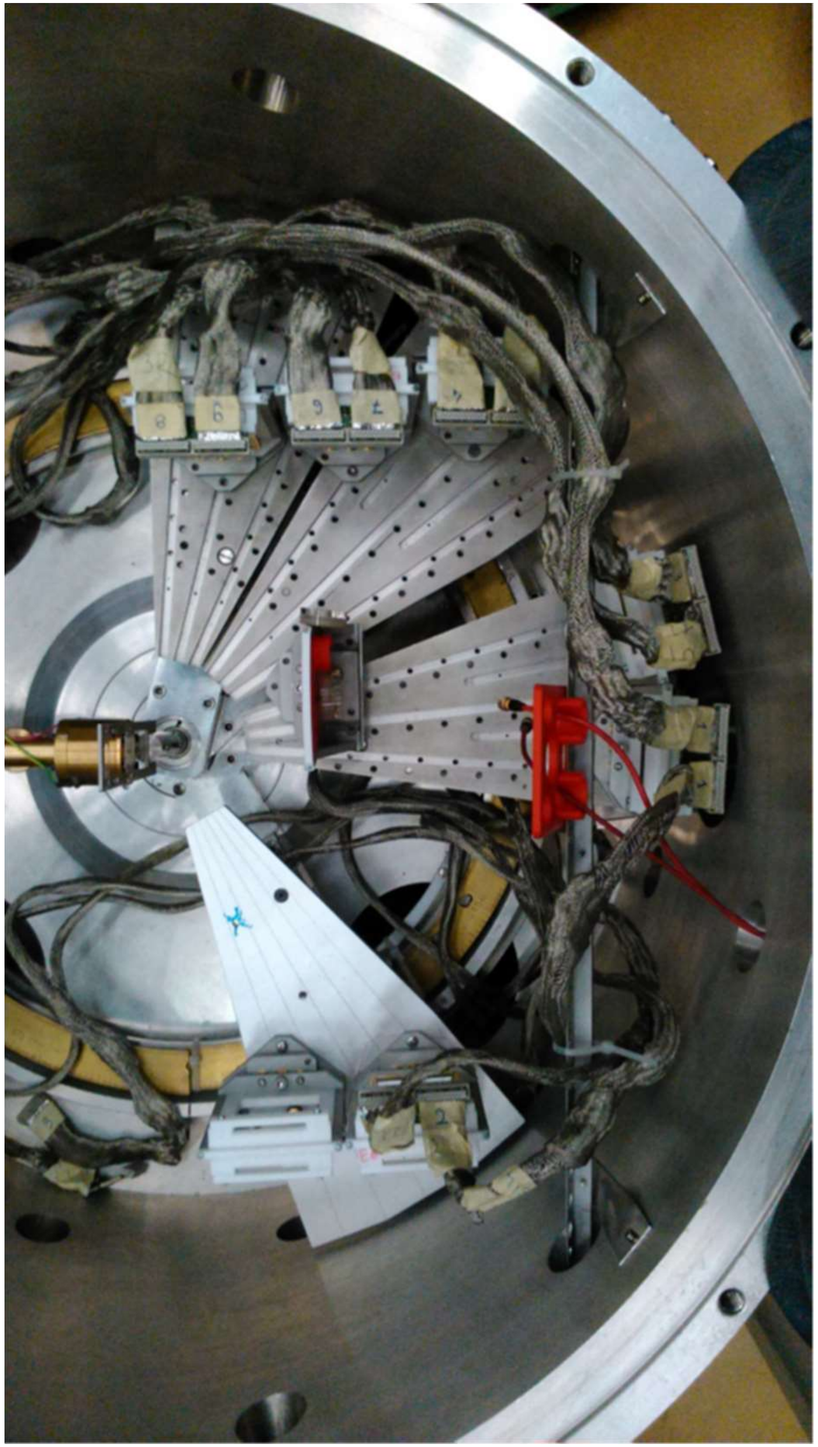


The ^{24} Mg excitation energy spectra from α's in the telescope



Beam energy

Spectra for all pixels together

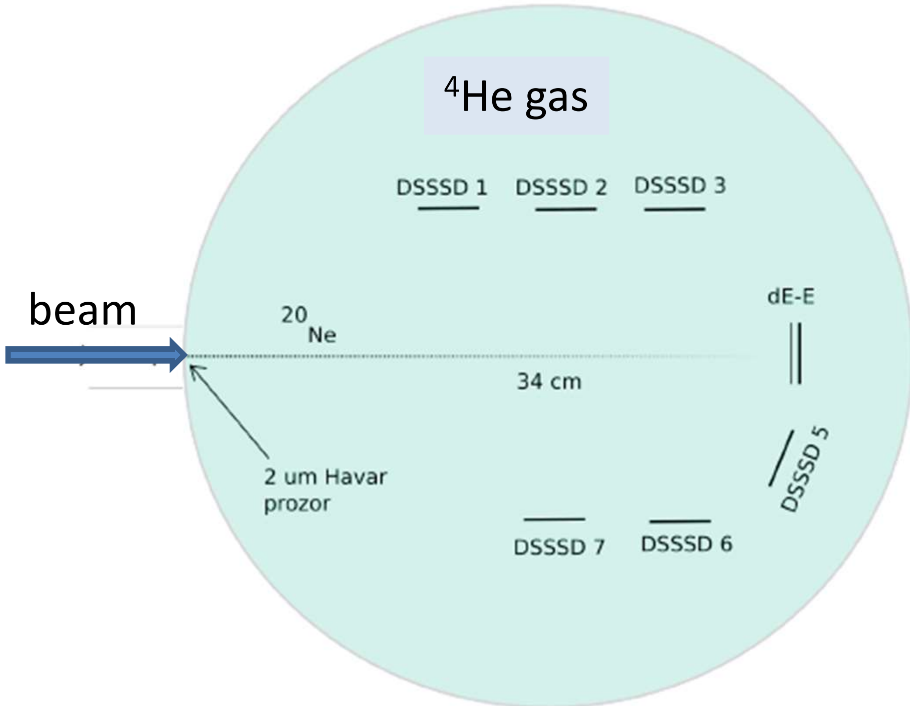


INFN - LNL Legnaro 2014

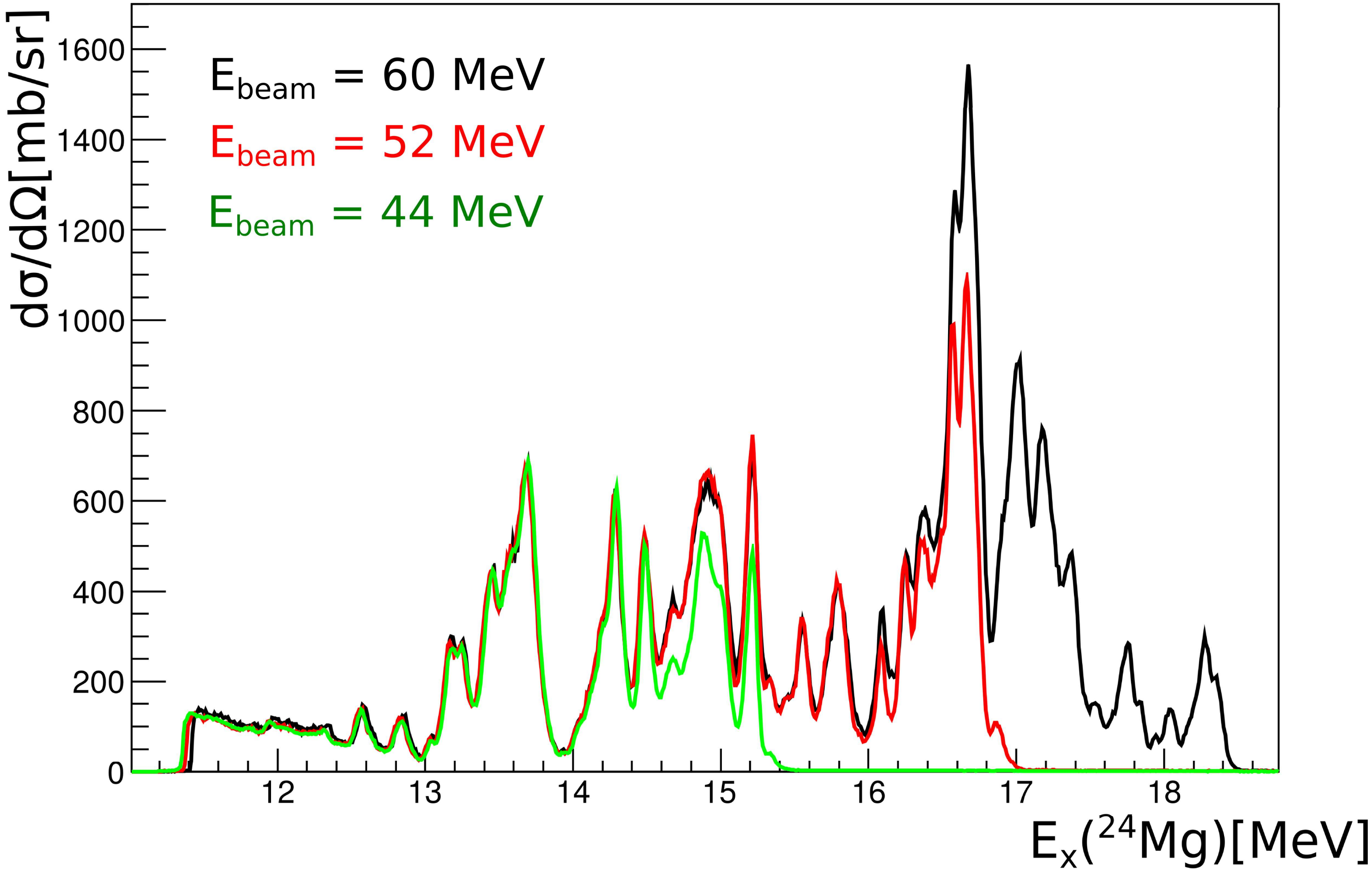
^{20}Ne beam from PIAVE + ALPI facility

LIRAS chamber

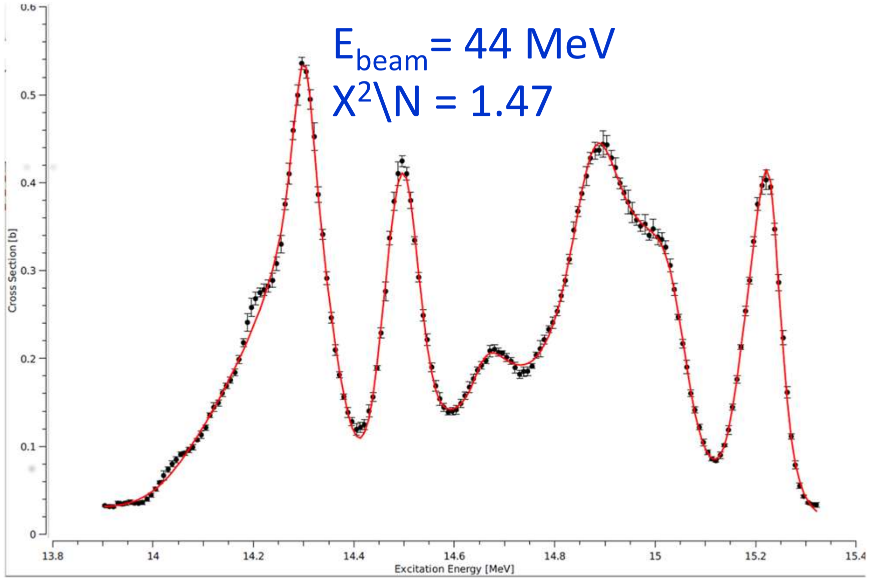
- entrance window: 2µm HAVAR foil
- ^{4}He gas target pressure up to 800 mbar
- beam stopped before the 0° telescope
- side detectors: scattered α's have low energy + energy loss and straggling in the gas – unresolved resonances

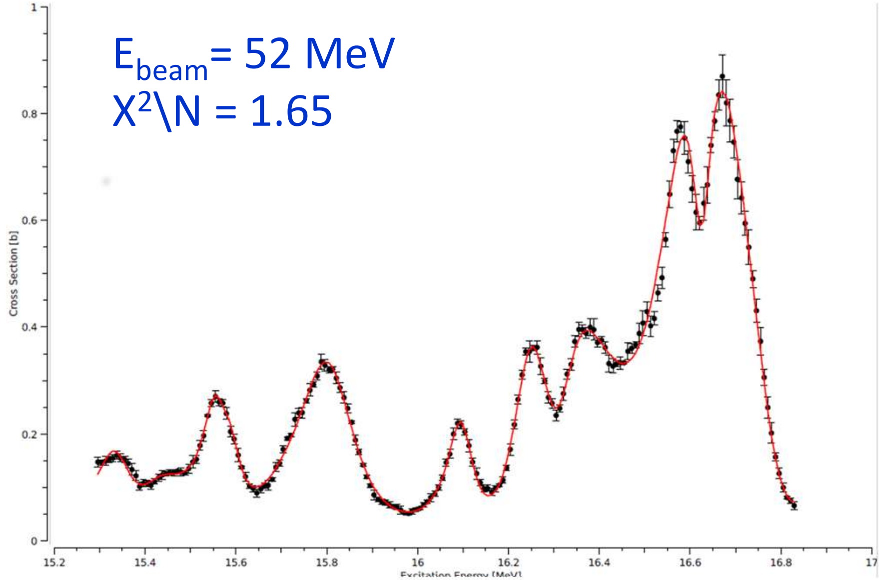


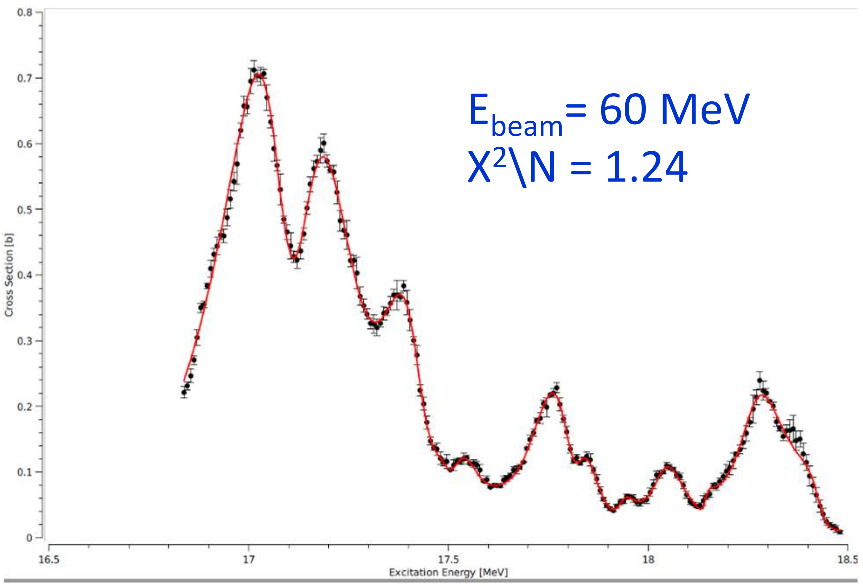
Detector telescope at 0 degree: normalized to previous GANIL measurements and efficiency corrected (±5°) data for three beam energies ($\theta_{CM}(^{24}Mg)=177°$)

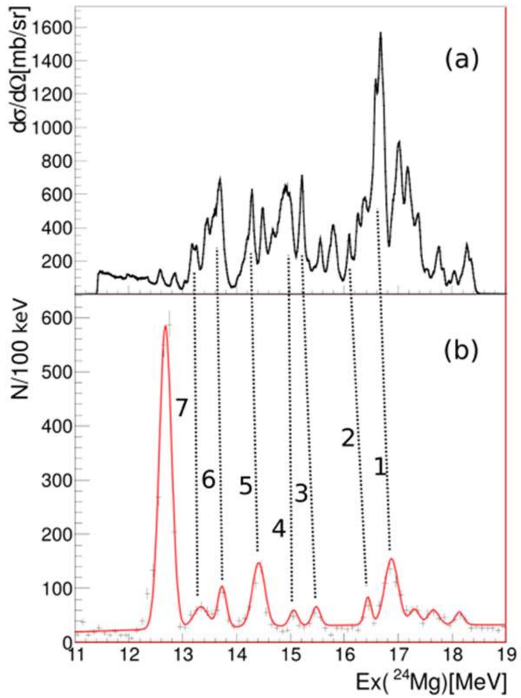


R-matrix fit









RDS

GTRS

Summary

- Clustering is important structural mode in light nuclei
- Clustering governs some key nuclear reactions for elements synthesis in astrophysical enviroments
- An Universe like ours would not be possible without clustering
- The origin of clustering is not fully understood yet, but it is a consequence of the basic principles of nature
- Improved experimental and theoretical results from nuclear physics and astrophysics are needed to pin down the origin of matter