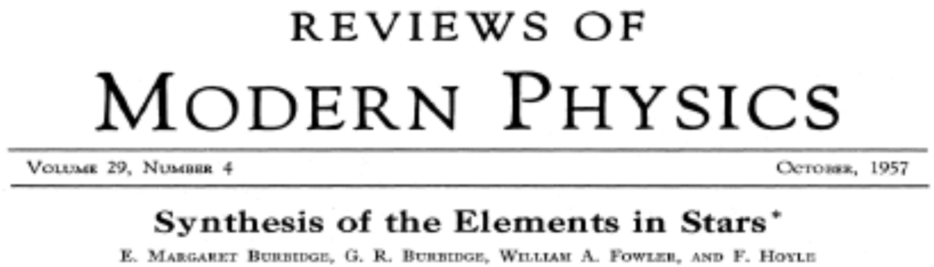
ECOS-EURISOL Joint Town Meeting,
Institut de Physique Nucléaire, 28-31 October 2014

Status and Perspectives in Nuclear Astrophysics

Aurora Tumino

... Everything starts from the B²FH review paper of 1957,
the basis of the modern nuclear astrophysics

this work has been considered as the *greatest gift of astrophysics* to modern civilization



REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

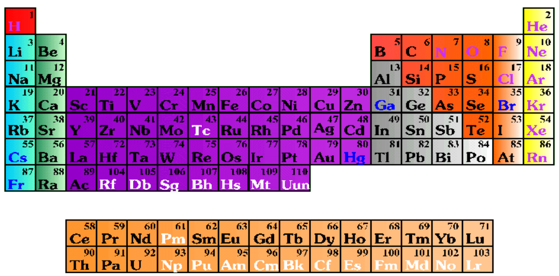
The first complete review of nuclear reactions explaining:
H and He quiescent and hot burning, and of the nucleosynthesis beyond Fe.

The elements composing everything from planets to life were forged inside earlier generations of stars!

Nuclear reactions responsible for both ENERGY PRODUCTION and CREATION OF ELEMENTS

(EXPERIMENTAL) NUCLEAR ASTROPHYSICS

- study energy generation processes in stars
- study nucleosynthesis of the elements



- What is the origin of the elements?
- How do stars/galaxies form and evolve?
- What powers the stars?
- How old is the universe?
- ...

NUCLEAR PHYSICS

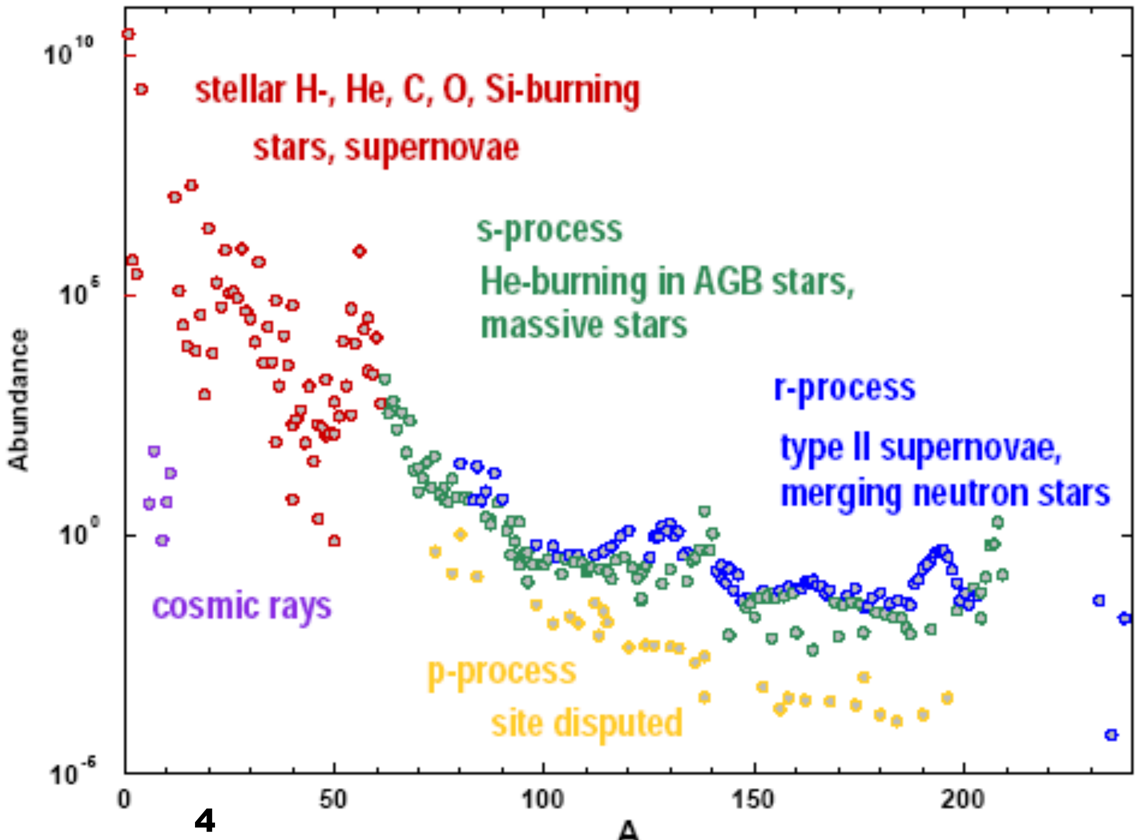
↓

KEY for understanding

MACRO-COSMOS intimately related to MICRO-COSMOS

The Synthesis of the Elements in stars

1. H burning → conversion of H to He
2. He burning → conversion of He to C, O …
3. C, O and Ne burning → production of A: 16 to 28
4. Si burning → production of A: 28 to 60
5. s-, r- and p-processes → production of A>60
6. Li,Be, and B from cosmic rays



from: M. Wiescher, JINA lectures on Nuclear Astrophysics stellar reaction rate $\langle \sigma v \rangle = \int \sigma(v)\phi(v) v dv$

need: a) velocity distribution $\phi(v)$

b) cross section $\sigma(v)$

a) velocity distribution

interacting nuclei in plasma are in thermal equilibrium at temperature T

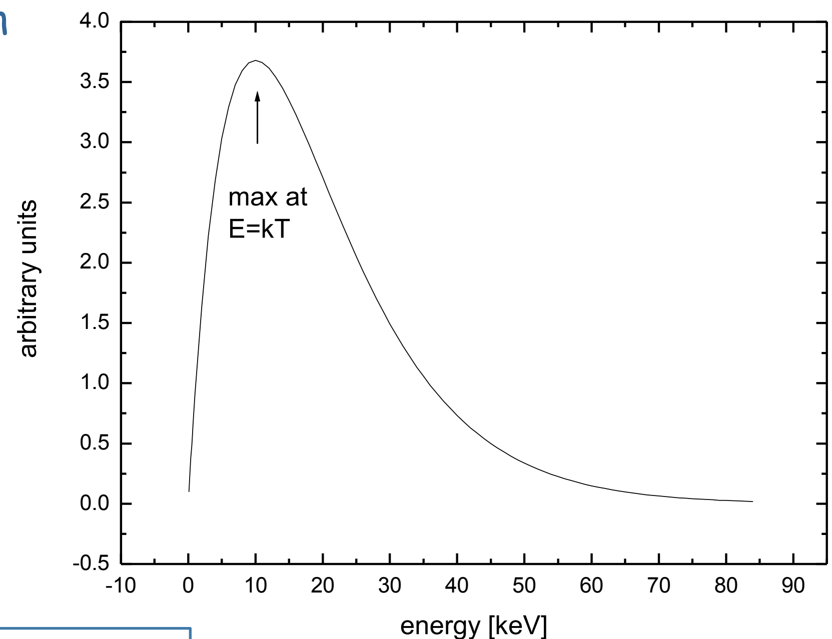
also assume non-degenerate and non-relativistic plasma

$\Rightarrow$ Maxwell-Boltzmann velocity distribution

$$\phi(v) = 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} v^2 \exp\left(-\frac{\mu v^2}{2kT} \right)$$

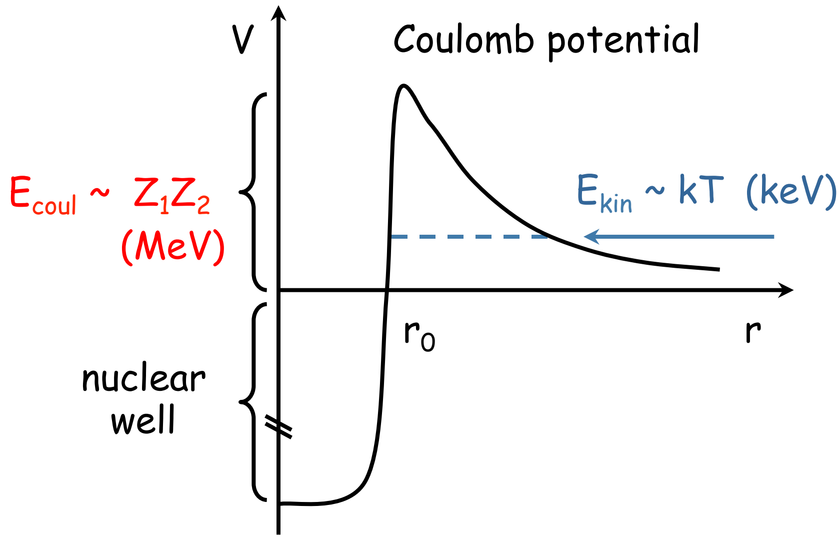
with $\mu = \frac{m_p m_T}{m_p + m_T}$ reduced mass

v = relative velocity



$kT \sim 8.6 \times 10^{-8}$ T[K] keV

example: Sun $T \sim 15 \times 10^6$ K $\Rightarrow$ kT ~ 1 keV charged particles ➡ Coulomb barrier



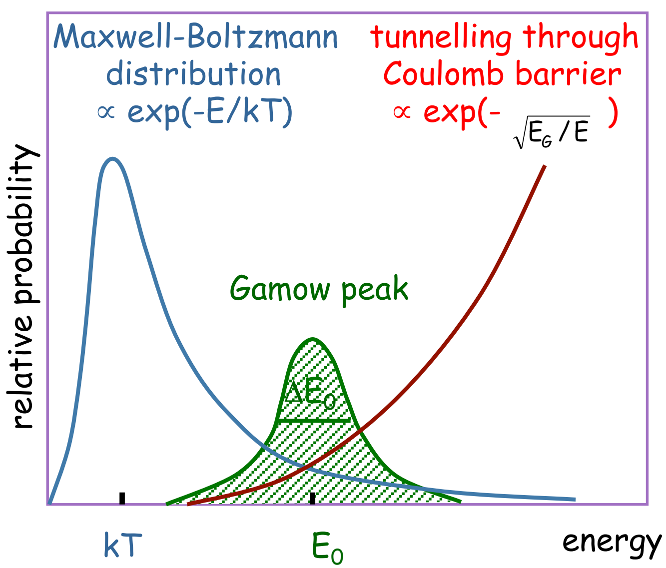
energy available: from thermal motion

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

$T \sim 15x10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

reactions occur through TUNNEL EFFECT

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



Gamow peak: energy of astrophysical interest where measurements should be carried out

$kT \ll E_0 \ll E_{coul}$

10^{-18} barn < σ < 10^{-9} barn

⬇

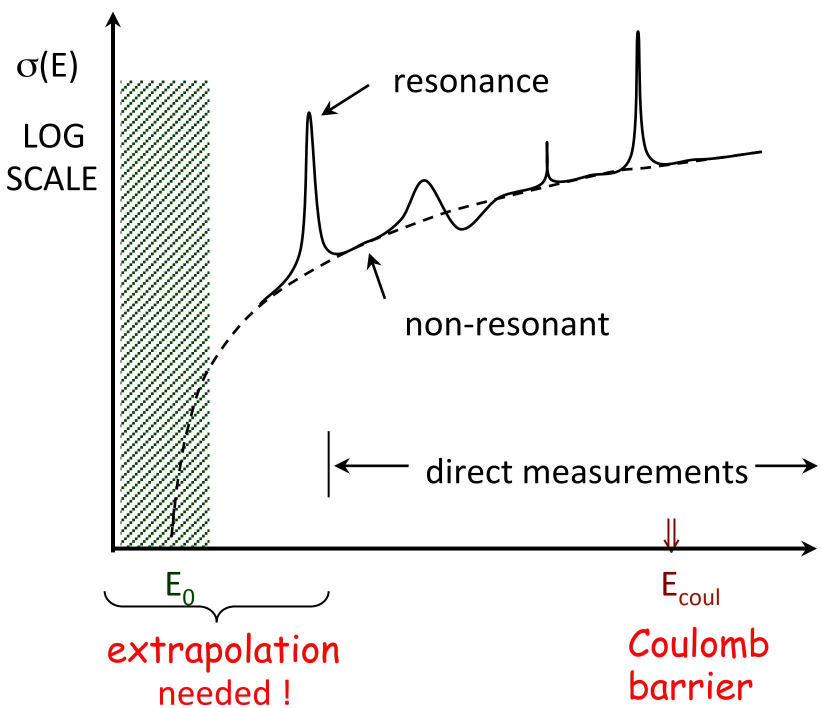
major experimental challenges

Experimental approach

measure $\sigma(E)$ over as wide a range as possible, then extrapolate down to E_0!

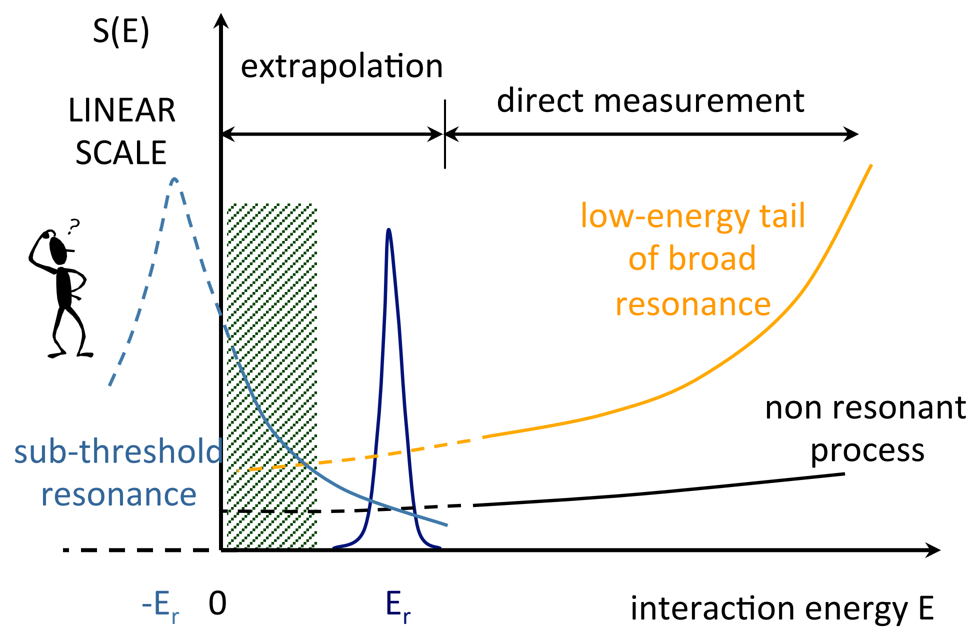
CROSS SECTION

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



S-FACTOR

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$



DANGER OF EXTRAPOLATION !

low cross sections → low yields → poor signal-to-noise ratio

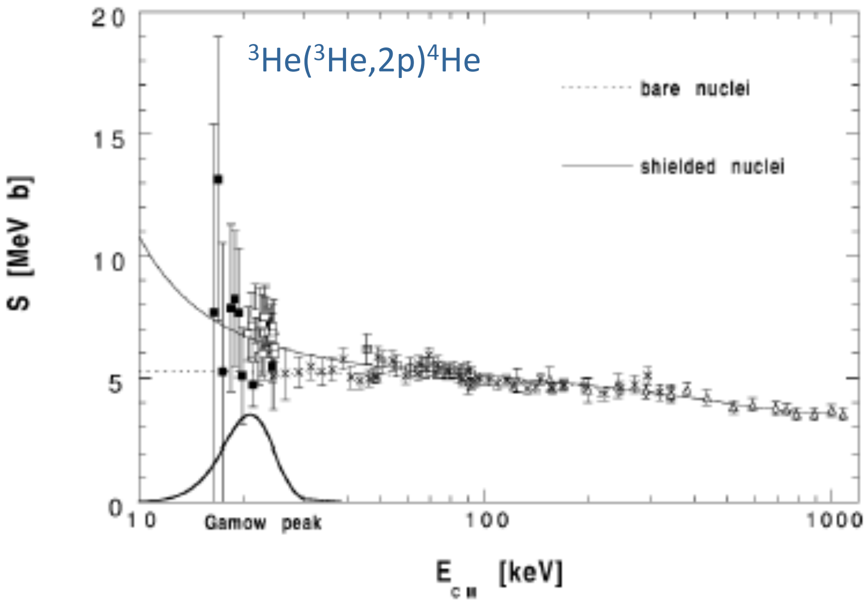
maximising the yield requires:

- improving "signal"
- high beam currents BUT limitations: charge confinement - heating effects on target
- thicker, purer targets BUT limitations: exponential drop of cross section high purities difficult + expensive
- reducing "noise" (i.e. background)
- combination of both

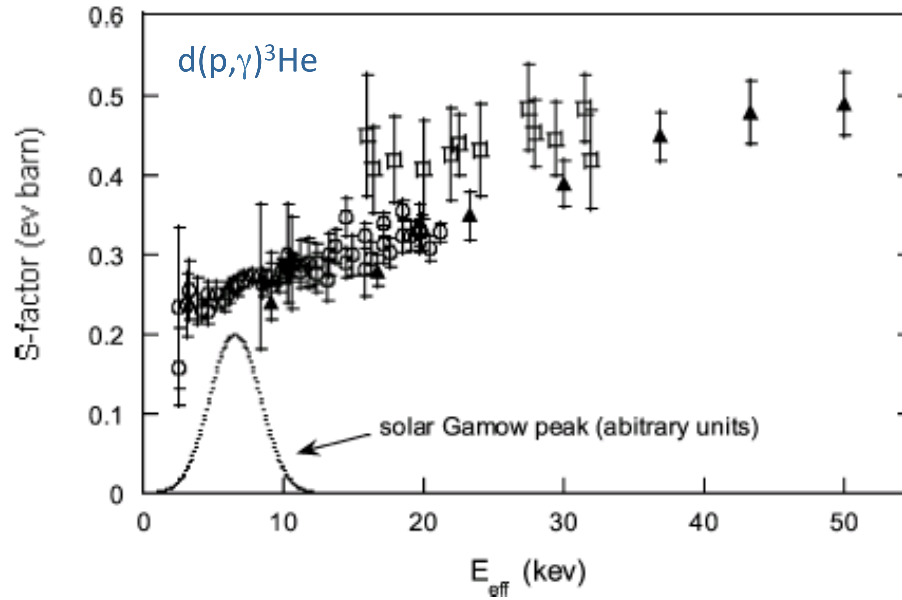
LUNA – Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp chain

R. Bonetti et al.: Phys. Rev. Lett. 82 (1999) 5205



C. Casella et al.: Nucl. Phys. A706 (2002) 203-216



@ lowest energy:

σ ~ 20 fb → 1 count/month

@ lowest energy:

σ ~ 9 pb → 50 counts/day

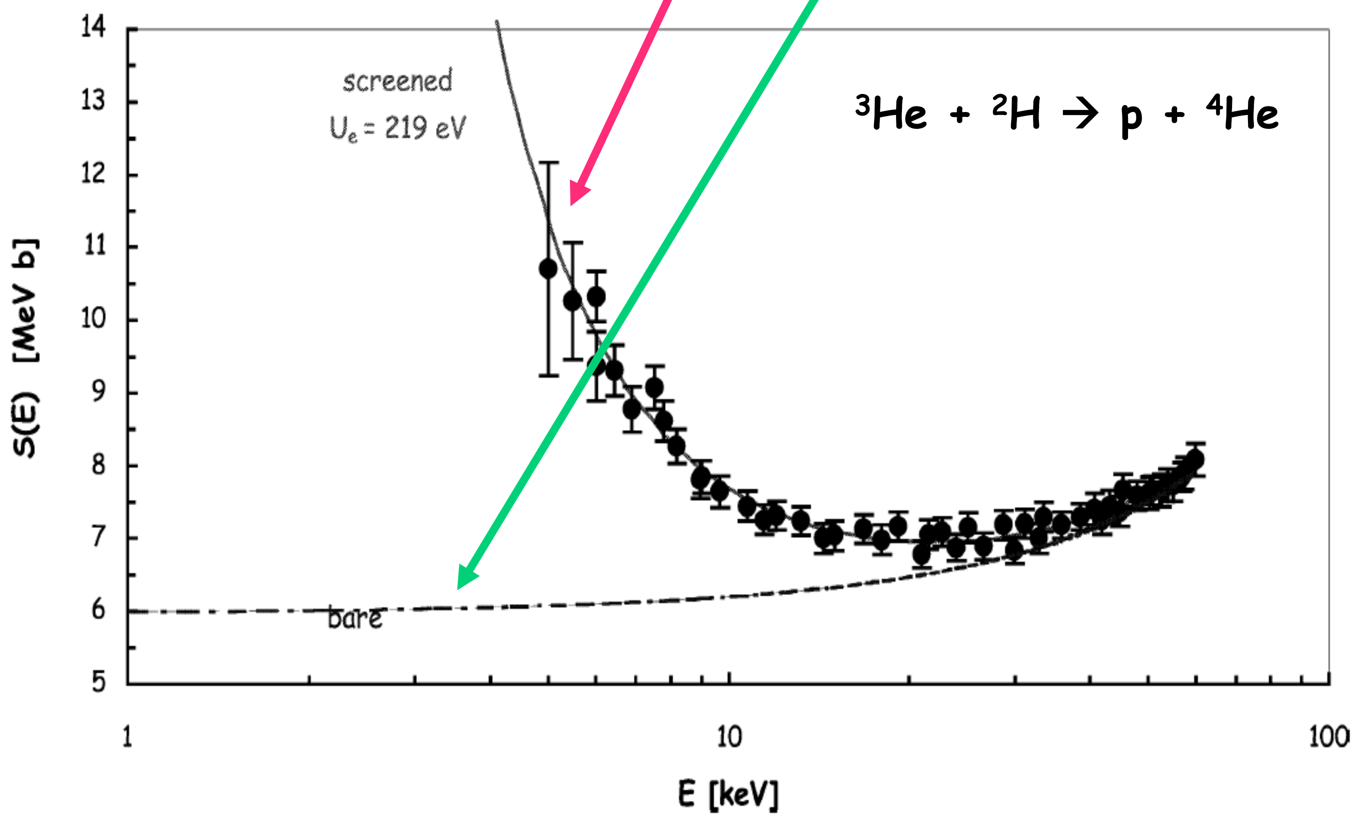
only two reactions studied directly at Gamow peak

Electron Screening

…but… further problem at astrophysical energies → → → →

S(E) enhancement experimentally found due to the Electron Screening

$$S(E)_s = S(E)_b \exp(\pi\eta U_e/E)$$



-> -> -> INDIRECT METHODS

- to measure cross sections at never reached energies (no Coulomb suppression), where the signal is below current detection sensitivity

- to get independent information on U_e

- to overcome difficulties in producing the beam or the target (Radioactive ions, neutrons..)

- NOTE: Measurements require careful validation. Data analysis needs nuclear reaction models

❖ **Coulomb dissociation**

…to determine the absolute S(E) factor of a radiative capture reaction **A+x → B+γ** studying the reversing photodisintegration process **B+γ → A+x**

❖ **Asymptotic Normalization Coefficients (ANC)**

… to determine the S(0) factor of the radiative capture reaction, **A+x → B+γ** studying a peripheral transfer reaction into a bound state of the B nucleus

❖ **Trojan Horse Method (THM)**

…to determine the S(E) factor of a charged particle reaction **A+x→c+C** selecting the Quasi Free contribution of an appropriate **A+a(x+s)→ c+C+s** reaction

Reactions measured so far at or near Gamow region:

$^{3}He(^{3}He,2p)^{4}He$ $^{1}H(p,g)^{3}He$ $^{14,15}N(p,g)^{15}O$ $^{3}He(^{4}He,g)^{7}Be$ $^{25}Mg(p,g)^{26}Al$

$^{2}H(^{4}He,g)^{6}Li$ $^{17}O(p,g)^{18}F$ $^{17}O(p,a)^{14}N$ ...

Many critical reactions for astrophysics BEYOND current capabilities

Some of the poorly known nuclear reactions with stable and photon beams

Heavy ion reactions: $^{12}C+^{12}C$, $^{16}O+^{16}O$, $^{12}C+^{16}O$
Neutron sources: $^{13}C(a,n)^{16}O$, $^{22}Ne(a,n)^{25}Mg$, $^{17}O(a,n)^{20}Ne$
Capture reactions: $^{3}He(a,\gamma)^{7}Be$, $^{12}C(a,\gamma)^{16}O$

Most of these reactions are resonant:

$$\langle \sigma v \rangle_{12} = \left(\frac{2\pi}{\mu_{12} kT} \right)^{3/2} \hbar^2 (\omega\gamma)_R \exp\left(-\frac{E_R}{kT} \right)$$

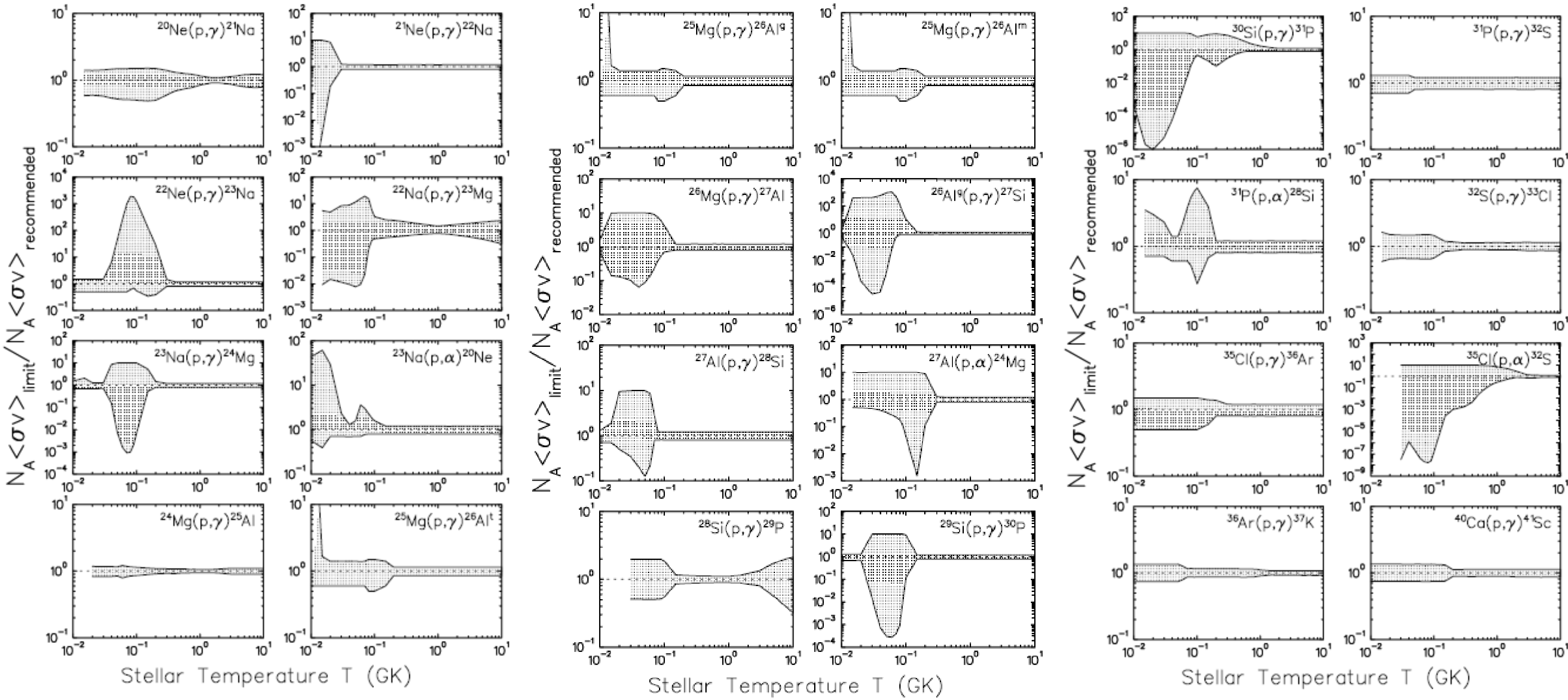
rate entirely determined by "**resonance strength**" $\omega\gamma$ and **energy of the resonance E_R**

NOTE

exponential dependence on energy means:

- small uncertainties in E_R (even a few keV) imply large uncertainties in reaction rate abundances of Ne, Na, Mg, Al, … in AGB stars and nova ejecta affected by many (p,γ) and (p,α) reactions

shaded areas indicate order of magnitude(s) uncertainties



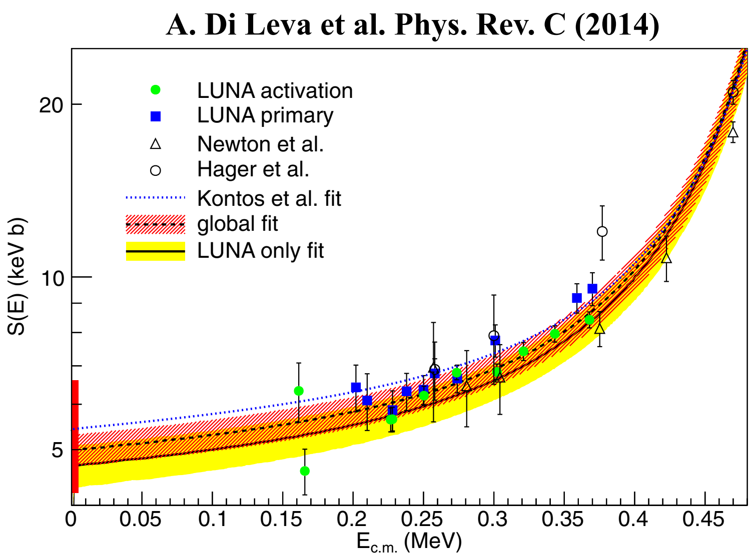
Iliadis et al. ApJ S134 (2001) 151; S142 (2002) 105; Izzard et al A&A (2007)

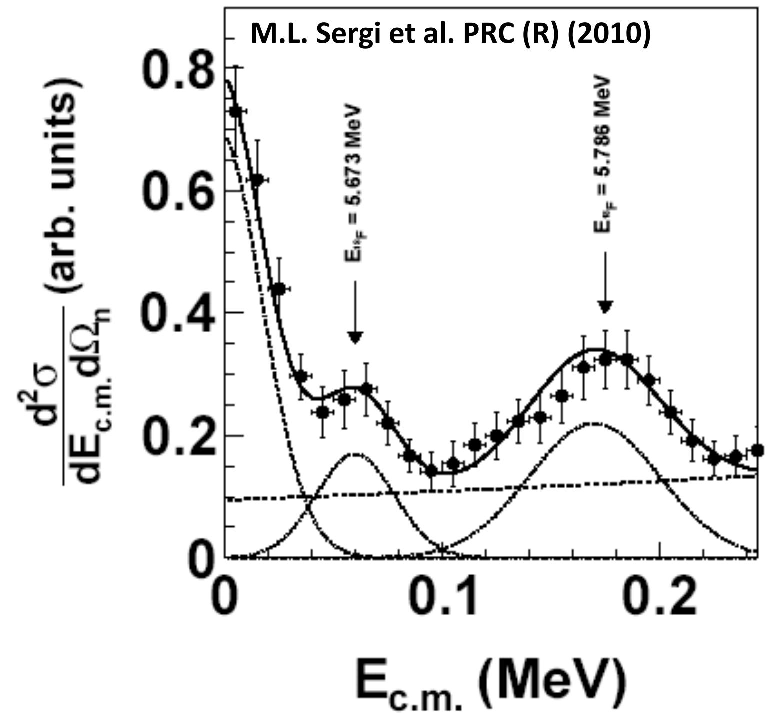
$^{17}O(p,\gamma)^{18}F$

Both reactions involved in the explosive hydrogen burning that powers classical novae and in the nucleosynthesis path of ^{18}F, of special interest in novae observations in the γ- ray wavelengths.

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

In explosive conditions, the reaction rate is dominated by contributions from narrow resonances at Ec.m.=65 and 183keV





$(\omega\gamma)_{183keV} = 1.67 \pm 0.12\ \mu eV$

$(\omega\gamma)_{65keV} = (3.66^{+0.76}_{-0.64}) \times 10^{-9}\ eV$

Reaction rate about 20% smaller than the most recent value reported in literature

The abundance of key isotopes such as ^{18}F, ^{18}O, ^{19}F, ^{15}N evaluated through nova models calculations, are now obtained with a precision of 10%

$^{13}C + \alpha \rightarrow n + ^{16}O$: recent THM experiment

Neutron source for the main component of the s-process, responsible for the production of most nuclei in the mass range 90<A<204

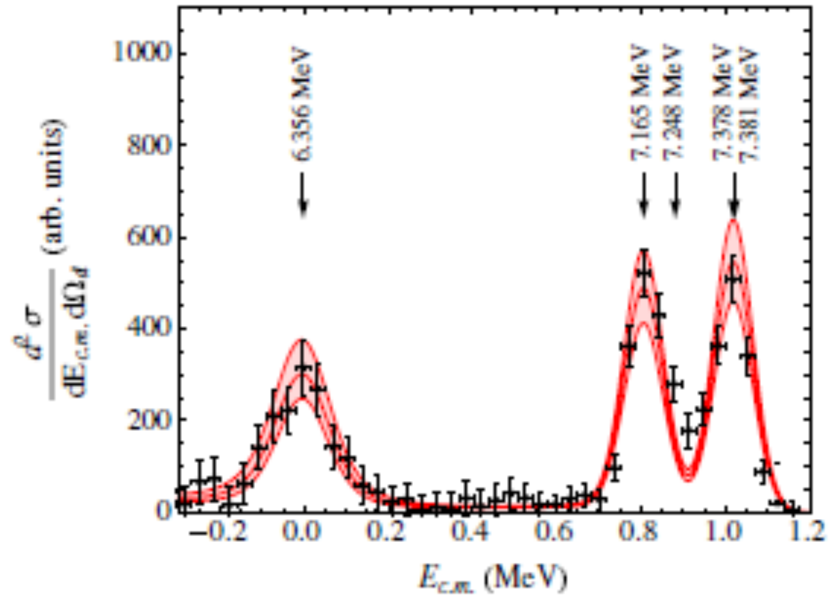
Active in He-burning shell in AGB from 140 to 230 keV → importance of the higher energy tail of the -3 keV resonance

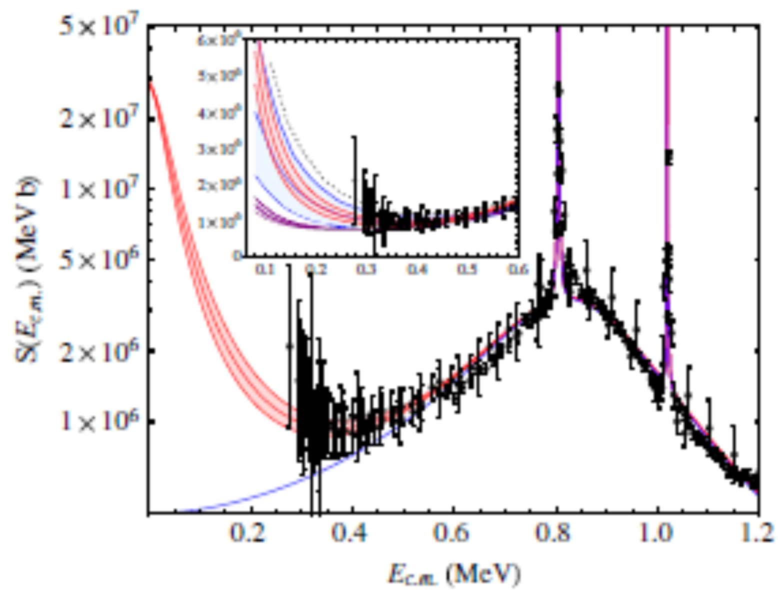
its new partial width $\Gamma_n^{1/2^+} = 83^{+9}_{-12}$ keV
and ANC $(\tilde{C}^{^{17}O(1/2^+)}_{\alpha-^{13}C})^2 = 6.7^{+0.9}_{-0.6}$ fm^{-1}

Reaction rate increases by a factor 3 in at T_9=0.01:
→30% variation in the abundance of

^{86}Kr, ^{87}Rb, ^{96}Zr, and ^{142}Ce

due to the increased neutron density!





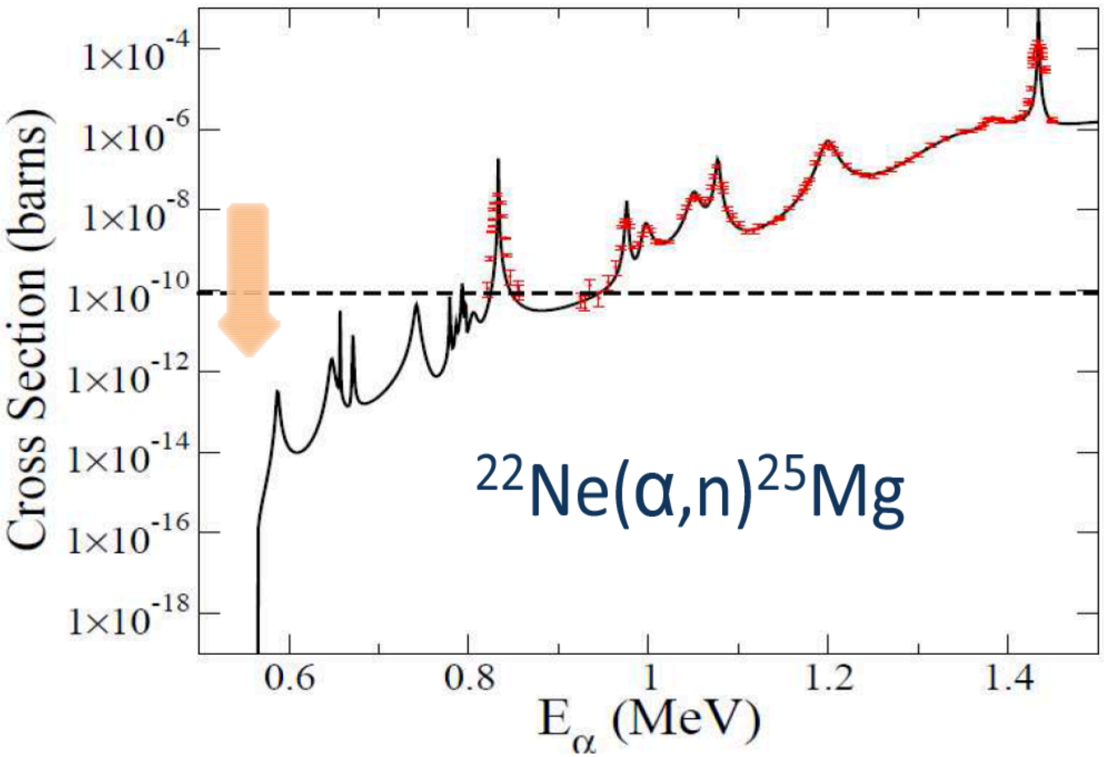
M. La Cognata et al., APJ 109 (2014) 232701

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

importance: s-process in AGB stars

astrophysical energies: 400 - 700 keV

current status minimum measured E: ~800 keV



suggestion for improvements of measurements: high intensity stable beams

inverse kinematics, indirect Methods

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

importance: evolution of massive stars

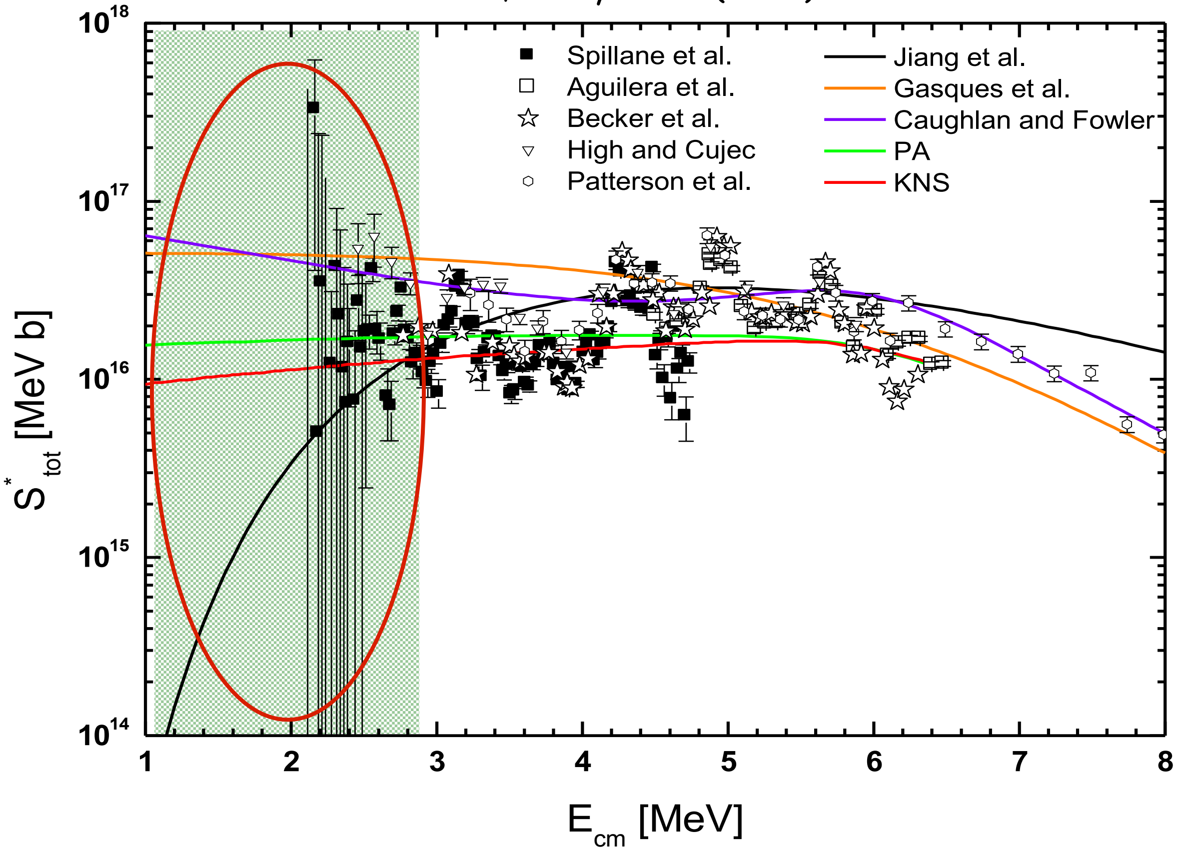
astrophysical energy: 1 – 3 MeV

minimum measured E: 2.1 MeV (by γ-ray spectroscopy)

extrapolations differ by
3 orders of magnitude

large uncertainties
in astrophysical models
of stellar evolution
and nucleosynthesis

Strieder, J. Phys. G35 (2008) 14009



options for improvements of measurements: high intensity stable beams,
indirect methods

THM Experiment for C-burning

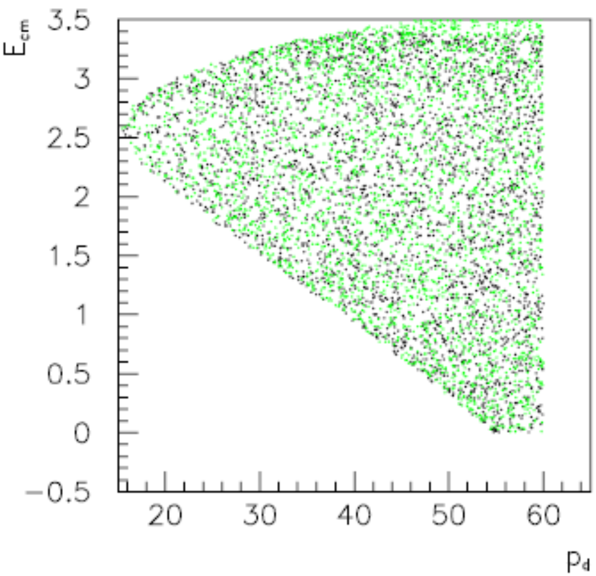
$^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions via the **<u>Trojan Horse Method</u>** applied to the *$^{12}C(^{14}N,\alpha^{20}Ne)^{2}H$ and $^{12}C(^{14}N,p^{23}Na)^{2}H$* three-body processes

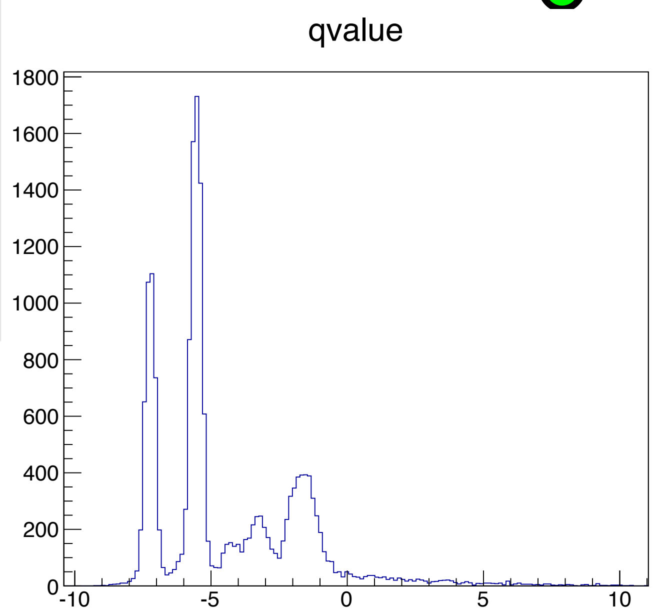
^{2}H from the ^{14}N as spectator s

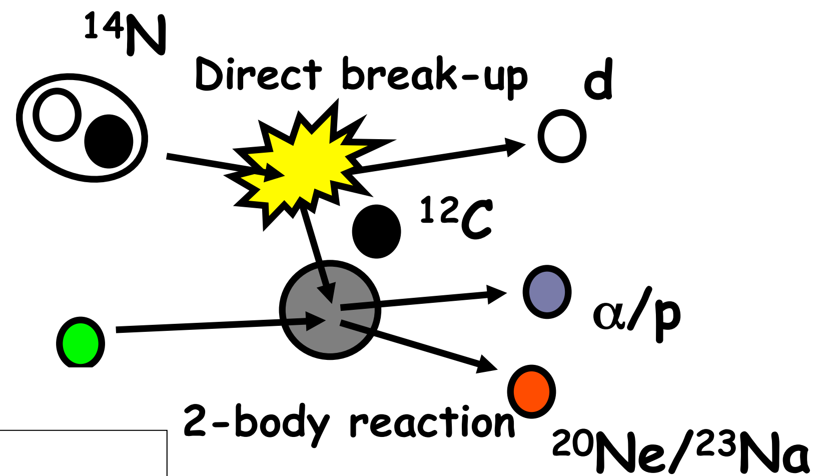
E_{14N} = 30 MeV

Observation of ^{12}C cluster transfer in the $^{12}C(^{14}N,d)^{24}Mg^{*}$ reaction (R.H. Zurmûhle et al. PRC 49(1994) 5)

^{12}C+ ^{12}C relative energy E_{cm} for a deuteron momentum ≤ 60 MeV/c







To be continued….

Thank you!