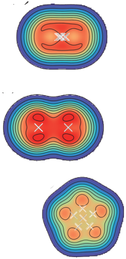
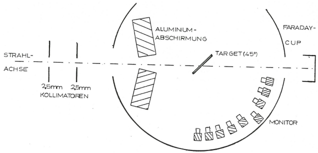
# Direct measurements of fusion reactions (with heavy ions) of astrophysics impact

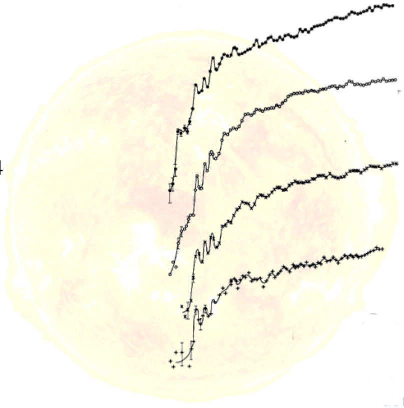
Marcel Heine

IPHC/CNRS Strasbourg

October 8, 2024

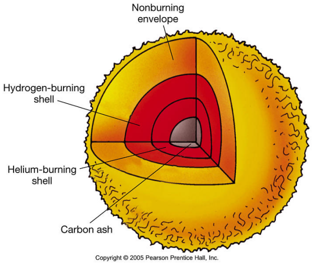


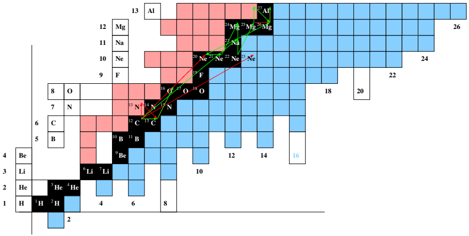


# Heavy ion reactions during carbon burning in massive stars

- $M \geq 8..10\ M_{\odot}$
- core made of oxygen and carbon
- Coulomb well




from A. Chieffi *et al.*, APJ **502** (1998), 737

$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow ^{24}\mathrm{Mg}$$

$$^{12}\mathrm{C} + ^{16}\mathrm{O} \rightarrow ^{28}\mathrm{Si}$$

$$^{16}\mathrm{O} + ^{16}\mathrm{O} \rightarrow ^{32}\mathrm{S}$$

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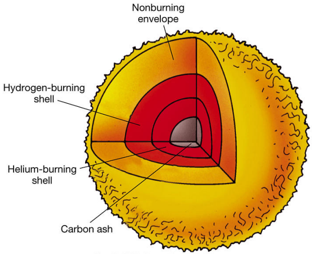




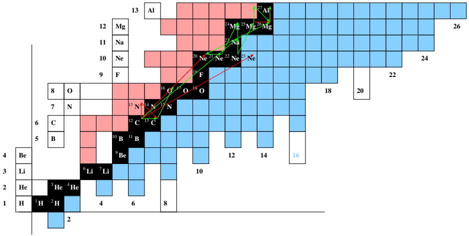

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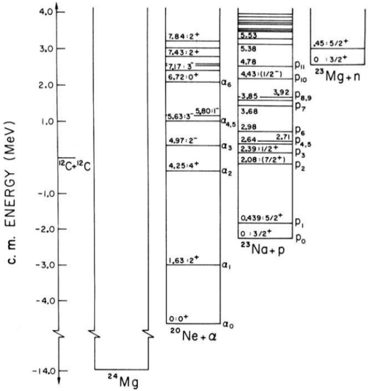
# Exit channels of light fusing systems: $^{12}$C+$^{12}$C




- *Q – value*
- $^{24}$Mg: compound nucleus

- measure particles
- measure gammas cascades!

- ground state: $\alpha_0$, p$_0$, *etc.*
- excited states: $\alpha_0, \alpha_1, \alpha_3, ..$

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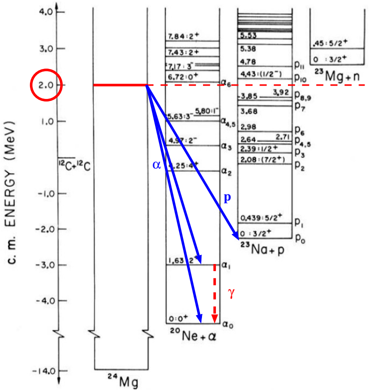


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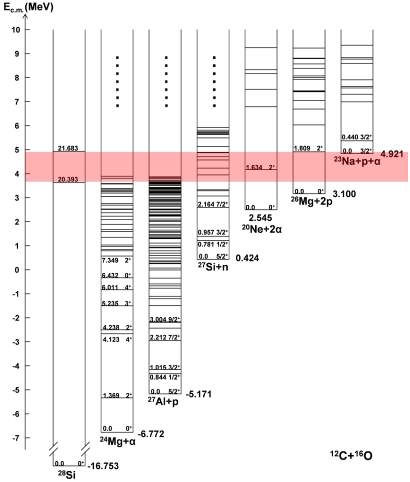
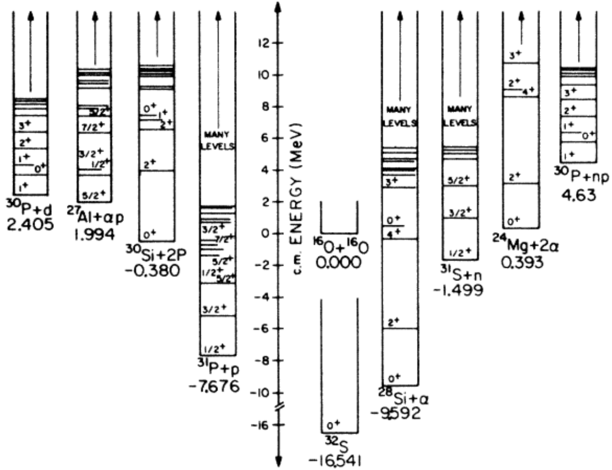



X. Fang *et al.*, PRC **96** (2017), 045804

# Exit channels of light fusing systems: $^{16}$O+$^{16}$O




J. Thomas *et al.*, PRC **33** (1986), 1679–1689

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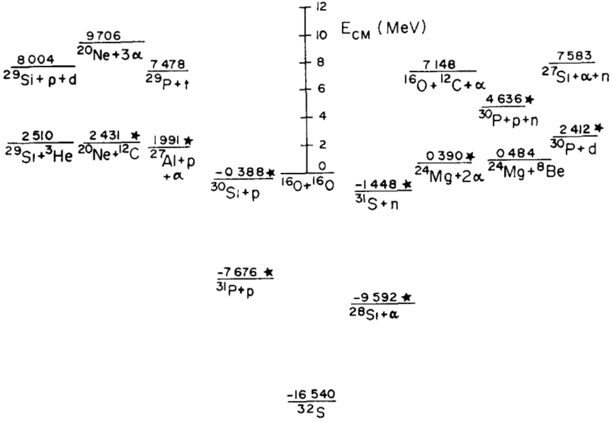



H. Spinka and H. Winkler, NPA **233** (1974), 456–494

# Comparing apples to oranges

number of open channels:

- $^{12}$C+$^{12}$C: $\sim$ 15
- $^{12}$C+$^{16}$O: $\sim$ 250
- $^{16}$O+$^{16}$O: $\sim$ 7000

- high number of states: gamma detection preferred
- $^{16}$O+$^{16}$O: statistical models employed
- accurate oxygen targets are hard to fabricate: systematic

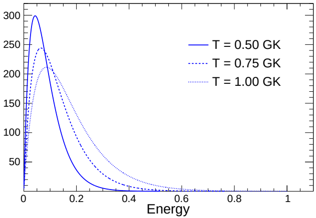
$\longrightarrow$ focus here on $^{12}$C+$^{12}$C

# Charged-particle-induced reactions for astrophysics

- reaction rate $\lambda$: number of reactions per volume and time

$$\mathrm{a} + \mathrm{A} \rightarrow \mathrm{b} + \mathrm{B}$$

$$\lambda = N_a N_A \langle v \cdot \sigma(v) \rangle$$




relative velocity $v$:

- Maxwell-Boltzmann distribution:

$$\Phi = \sqrt{\frac{8m}{\pi (k_\mathrm{B} T)^2}} E \exp(-E/k_\mathrm{B} T)$$

exponential drop

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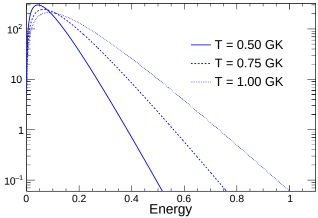


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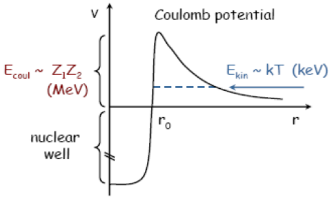
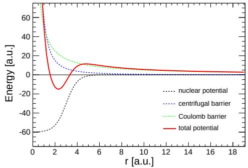



cross section $\sigma(v)$:

- energy $E$ inferior to Coulomb barrier $V_C$



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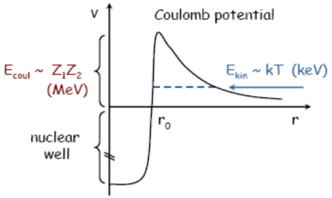
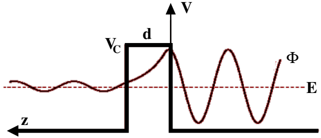



cross section $\sigma(v)$:

- transmission probability:

$$\hat{T} \approx \exp\left(-\frac{2\pi}{\hbar}\sqrt{\frac{m}{2E}} Z_{\mathrm{a}} Z_{\mathrm{A}} e^2\right) = \mathrm{e}^{-2\pi\eta}$$

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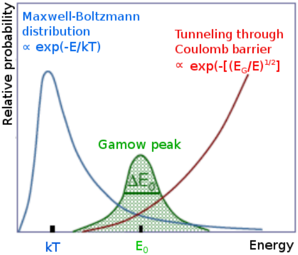



Gamow peak:

- reaction takes place at this energy

convolution of:

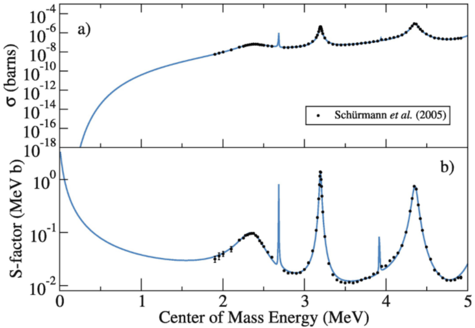
- Maxwell-Boltzmann distribution: $e^{-E/k_B T}$
- tunnelling probability: $e^{-2\pi\eta}$

# Our tools during this talk

- reaction rate $\lambda$
- Gamow peak/window
- *S*-factor:

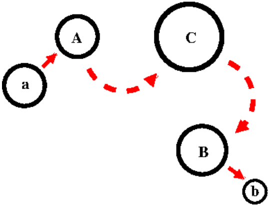
  $S(E) = \sigma(E) E \exp(2\pi\eta)$

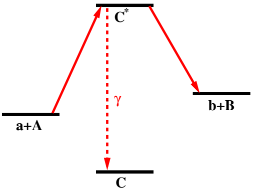
- cancel barrier transmission term
- display "nuclear structure" →




D. Schürmann *et al.*, PLB **711** (2012), 35–40

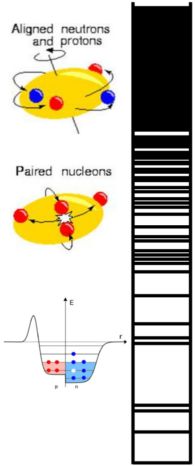
# a+A → C* → b+B




- energy $E_a$ fully absorbed in compound C
- particles a and A indistinguishable

$a+A \rightarrow C^{*} \rightarrow b+B$




compound

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particle-hole excitation:

- single particle excitation
- rotational bands

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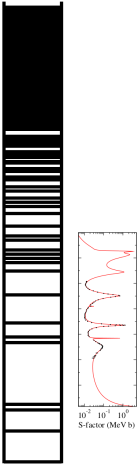


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- 1 eV$\geq$ $\Gamma \leq$ 1 MeV
- isolated states
- overlapping widths
- continuum

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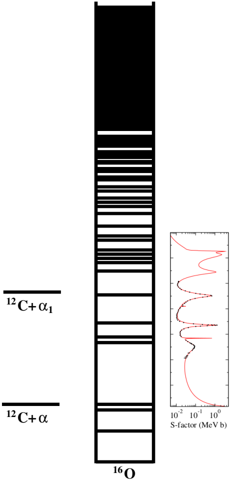


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$^{12}C(\alpha, \gamma)^{16}O$

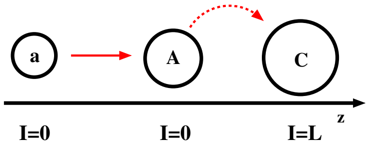
- resonances at thresholds

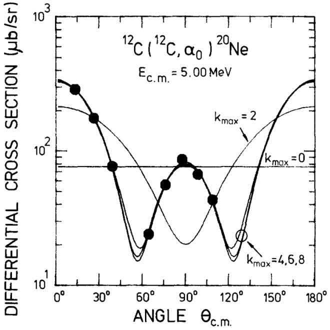
# Angular momentum conservation and angular distributions

N. Bohr hypothesis of independence: compound formation and decay are independent

but angular momentum conservation

fusion of spinless particles:




- L perpendicular to z
- equal probability ± z

$$\left(\frac{d\sigma}{d\Omega}\right) = \sum_{k=0}^{k_{max}} a_k P_k(\cos(\theta)),\ k = 0, 2, 4, ..$$

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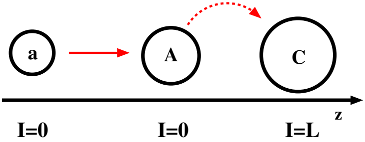


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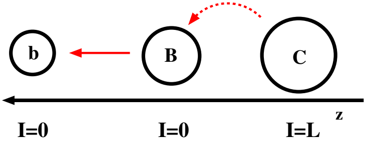


→ compound state spin from fusion measurements

- normalisation of cross sections: $P_0(\cos(\theta))$

# Fusion formation and population of compound states

identical $0^+$ particles:

$$^{12}\mathrm{C} + ^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^*$$
$$0^+ + 0^+ \rightarrow \quad ??$$

wave function:

$$|\Psi\rangle = |\Phi\rangle_{\mathrm{space}} \otimes |\Phi\rangle_{\mathrm{spin}} \otimes |\Phi\rangle_{\mathrm{isospin}}$$
$$|\Phi\rangle_{\mathrm{space}} = R_n(r)\, Y_l^m(\theta, \phi)$$
$$Y_l^m(\pi - \theta, \phi + \pi) = -1^l\, Y_l^m(\theta, \phi)$$
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parity is multiplicative:

$$P_{\mathrm{Mg}} = -1^l\, P_{\mathrm{C}} \cdot P_{\mathrm{C}}$$

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| This work | | | Previous work | | | | |
|---|---|---|---|---|---|---|---|
| $E$ (MeV) | $\Gamma_{\mathrm{el}}$ (keV) | $\Gamma_{\mathrm{tot}}$ (keV) | $l$ | $E$ (MeV) | $\Gamma_{\mathrm{el}}$ (keV) | $\Gamma_{\mathrm{tot}}$ (keV) | Ref. |
| 4.25 | 0.4 | 80 | 0 | 4.25 | | 60–80 | [3] |
| (5.71) | 35 | 70 | (0) | | | | [3] |
| 5.80 | 2.37 | 50 | 0 | 5.82 | | 50 | [13] |
| 5.97 | 9.0 | 50 | 0 | 5.97 | | 50 | [13] |
| 4.64 | 0.04 | 40 | 2 | 4.62 | | 60–80 | [3] |
| 4.865 | 1.0 | 80 | 2 | 4.88 | | 80 | [3] |
| 4.99 | 2.0 | 100 | 2 | 5.00 | | 60–80 | [3] |
| 5.38 | 1.4 | 80 | 2 | 5.37 | | 60–80 | [3] |
| 5.66 | 6.0 | 50 | 2 | 5.64 | | 140 | [3] |
| | | | 2 | 5.6 | 20 | 104 | [54] |
| | | | 2 | 5.6 | 10 | 130 | [55] |
| 5.78 | 0.38 | 60 | 2 | 5.8 | | 60 | [13] |
| 6.01 | 6.2 | 50 | 2 | 6.01 | | 70 | [13] |
| 6.29 | 15 | 60 | 2 | 6.25 | | 60–80 | [3] |
| | | | | 6.28 | ⩾16 | 125 | [7] |
| 6.65 | 11 | 50 | 2 | 6.64 | 29 | 100 | [55] |
| | | | | 6.63 | 40 | 100 | [7] |
| 4.44 | | 60 | 4 | 4.46 | | 60–80 | [3] |
| | 0.045 | | | | | | |
| 5.75 | 0.06 | 60 | 4 | 5.77 | | 60 | [13] |
| 5.95 | 1.5 | 50 | 4 | 5.92 | 4 | 60 | [3] |
| | | | | 5.96 | ⩾3 | 100 | [7] |
| | | | 4 | 5.94 | | 50 | [13] |
| | | | | | 3.75 | | |
| | | | 4 | 6.0 | 7.5 | 88 | [54] |
| | | | 4 | 6.0 | 4 | 100 | [55] |
| 6.49 | 0.4 | 50 | (6) | 6.49 | | ⩾50 | [7] |

E.F. Aguilera *et al.*, PRC **73** (2006), 064601

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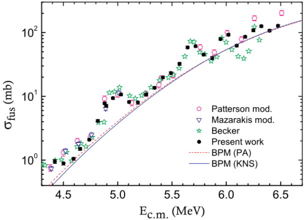
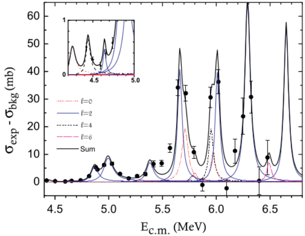
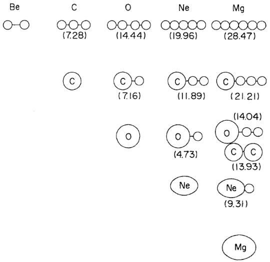



E.F. Aguilera *et al.*, PRC **73** (2006), 064601

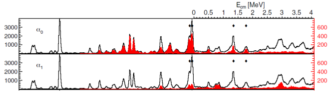
# Near threshold resonances in $^{24}$Mg: "extending the Hoyle paradigm"

- the Hoyle state (1954, 1957)
- $\alpha$-cluster configuration of $^{12}$C
- resonance at $^{8}$Be+$\alpha$ threshold



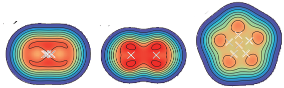

K. Ikeda *et al.*, SPTP **E68** (1968), 464–475

- excitation of carbon fusion compound:
- $^{24}$Mg($\alpha$, $\alpha'$)$^{24}$Mg$^*$ at iThemba




P. Adsley *et al.*, PRL **129** (2022), 102701

- $0^+$ at 13.8 MeV ($^{12}$C$^{12}$C)
  $0^+$ at 15.3, 15.7 MeV (2$\alpha$$^{16}$O)
- isoscalar monopole excitations:

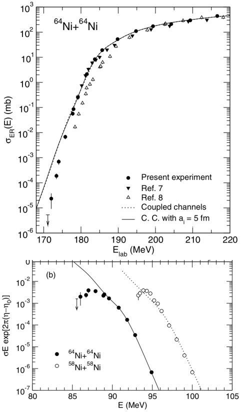


Y. Chiba and M. Kimura, PRC **91** (2015), 061302(R)

- close to threshold of sub-systems (alpha conjugate nuclei)
- challenging to access in direct experiments

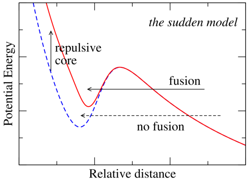
# So there are resonances. What else? $\hookrightarrow$ Fusion hindrance

evidenced for $Q \leq 0$ systems:




C.L. Jiang *et al.*, PRL **93** (2004), 012701

- seen also in $Q \geq 0$ systems
- repulsive core:




C.L. Jiang *et al.*, EPJ A **57** (2021), 235

- Pauli repulsion in symmetric systems
- density of states in $^{24}$Mg

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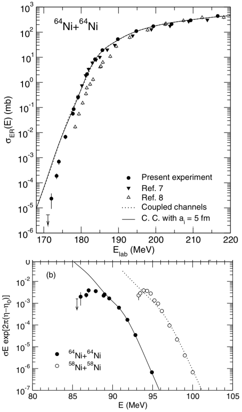
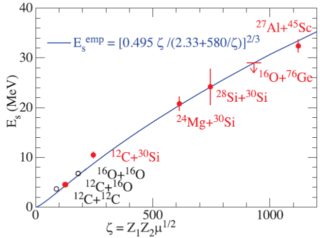



C.L. Jiang *et al.*, PRL **93** (2004), 012701

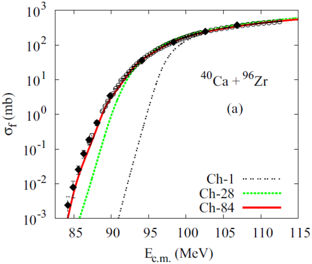
- $S$-factor develops maximum
- deep sub-barrier energies systematic:
- 4-parameter phenomenological model



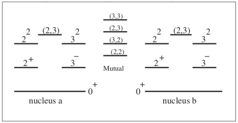

G. Montagnoli *et al.*, PRC **97** (2018), 024610

# Low-lying states contributing to sub Coulomb barrier fusion

Coupled Channel calculations:




H. Esbensen *et al.*, PRC **93** (2016), 034609




B.B. Back *et al.*, RMP **86** (2014), 317-360

first excited state:

- $^{40}$Ca: 3.4 MeV
- $^{96}$Zr: 1.6 MeV

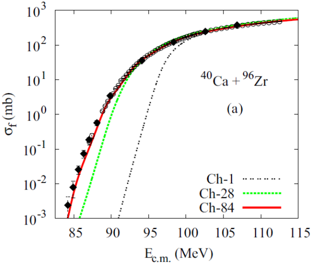
light nuclei:

- $^{12}$C: 4.4 MeV
- $^{16}$O: 6.0 MeV

- stiff nuclei (closed shell configuration $^{16}$O)
- low fusion cross sections
- broad *S*-factor maximum (if exists)

# Low-lying states contributing to sub Coulomb barrier fusion

Coupled Channel calculations:

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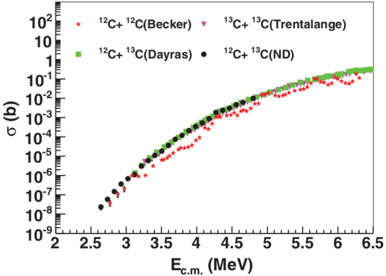
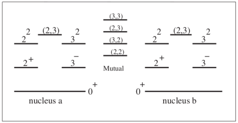



M. Notani *et al.*, PRC **85** (2012), 014607

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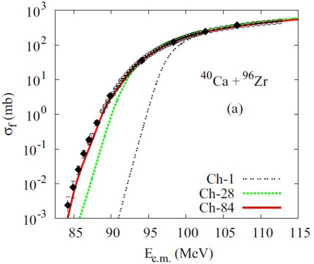


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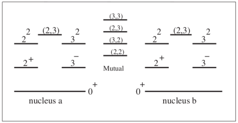


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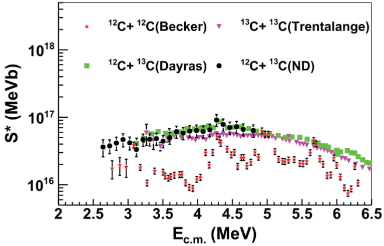


M. Notani *et al.*, PRC **85** (2012), 014607

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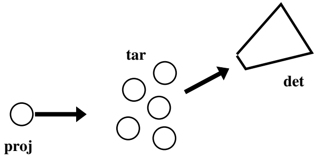
# Direct cross section measurements




$$\sigma(E) = \frac{N_{\text{reac}}/t}{N_{\text{proj}}/t \cdot N_{\text{tar}}/A} \cdot \Delta\Omega \cdot \epsilon$$

- projectiles: high intensity accelerator
- target:
  foils ($\sim$ 200 nm): moderate heating
  backings or graphite/oxides: cooling essential
- detectors:
  particle: $\Delta\Omega \sim 30$ %, $\epsilon = 100\%$
  gamma: $\Delta\Omega \sim 20$ %, $\epsilon = 2\%$

← background

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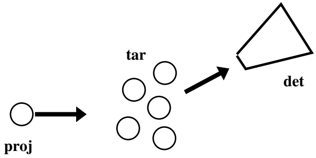


$$\sigma(E) = \frac{N_{\text{reac}}/t}{N_{\text{proj}}/t \cdot N_{\text{tar}}/A} \cdot \Delta\Omega \cdot \epsilon$$

- beam impurity
- target purity ($H_2O$)
- primordial, $^{40}$K
- cosmic

- projectiles: high intensity accelerator
- target:
  foils ($\sim$ 200 nm): moderate heating
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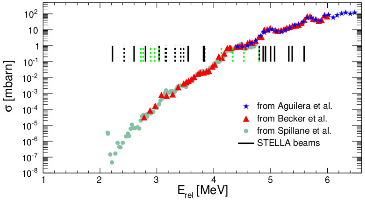
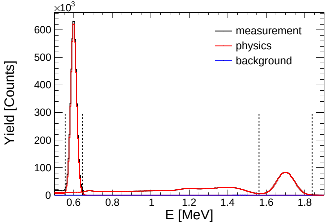
← background

# Typical fusion excitation function into low-count acquisition runs

sub barrier $^{12}C+^{12}C$:



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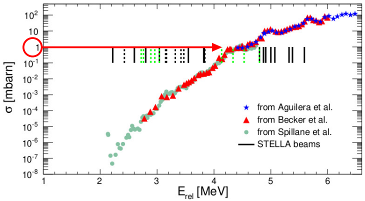


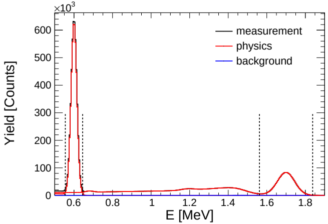


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  well defined peaks, $\pm 3\sigma$ gates

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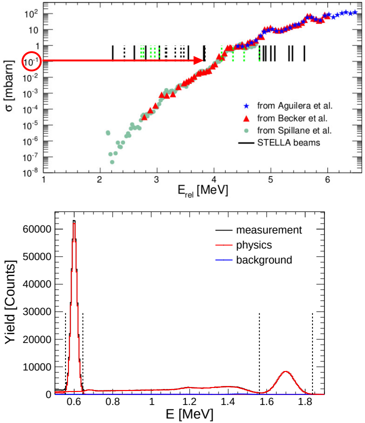


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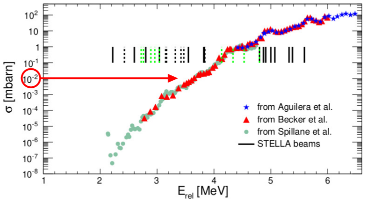


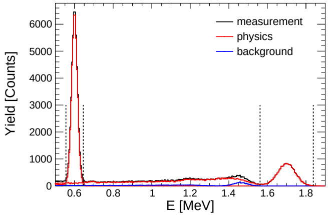


- physics: 0.6 MeV, 1.7 MeV
  well defined peaks, $\pm 3\sigma$ gates
- background: 1.46 MeV
  background model: linear, exponential

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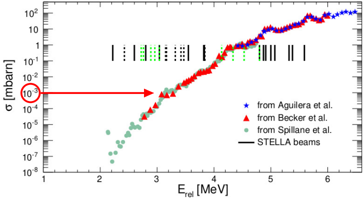


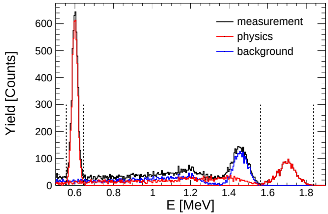


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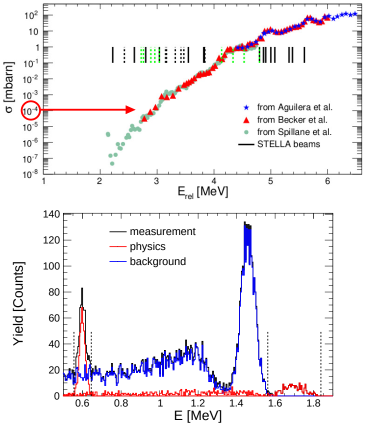


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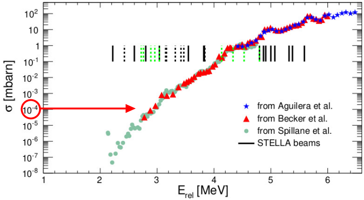


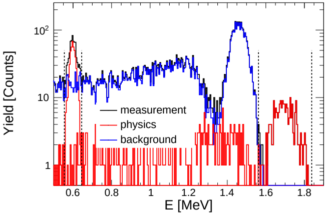


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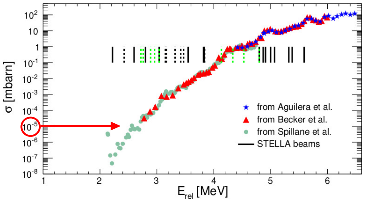


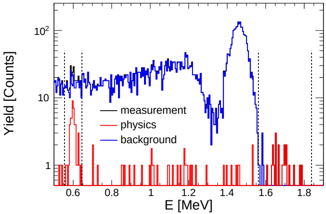


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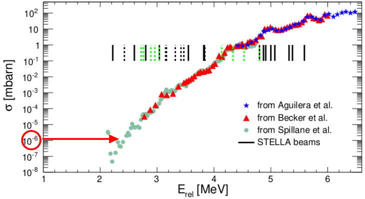


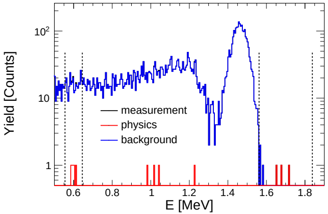


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  well defined peaks, $\pm 3\sigma$ gates
- background: 1.46 MeV
  background model: linear, exponential

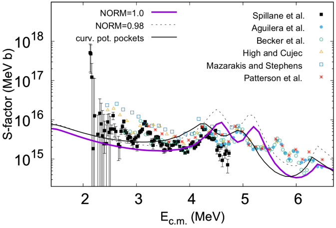
- statistical uncertainty
- tails of background contributions

- few counts statistic
- background fluctuations

# Brainstorming measurements in the astrophysics region of interest

astrophysics region of interest:

- 8..10 $M_\odot$ : 1.5 ± 0.3 MeV
- 25 $M_\odot$ : 2.25 ± 0.5 MeV




A. Diaz-Torres *et al.*, PRC **97** (2018), 055802

- strong fluctuations of the excitation function
  - → increase of reaction rate
  - extrapolations uncertain
  - experimental resolution needed
- possible fusion hindrance with broad maximum
  - → ceasing of reaction rate
  - ? phenomenological model suited
- low cross sections of stiff nuclei
  - → decrease of reaction rate
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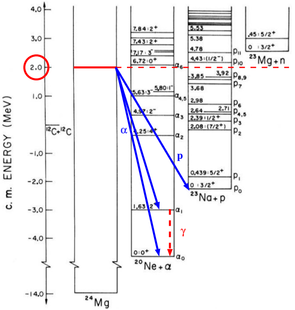
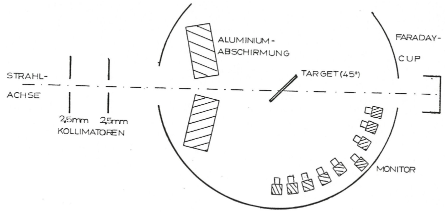
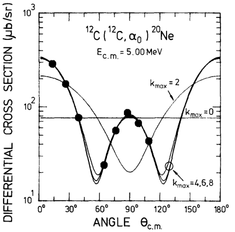


# Charged particle measurements by Becker *et al.*




H.W. Becker, diploma thesis (1978)

- $E_{\mathrm{c.m.}} = 2.8 - 6.3$ MeV
- $I = 1 - 5$ p$\mu$A
- targets: 8-30 $\mu$g/cm$^2$
- position granularity
- wide angular coverage
- resonance spectroscopy
- branching $^{12}$C+$^{12}$C




H.W. Becker *et al.*, ZPhys **303** (1981), 305-312

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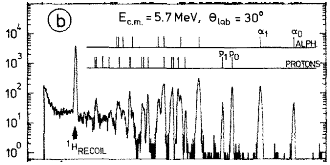

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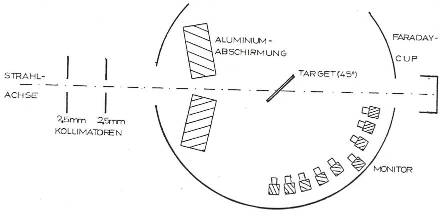


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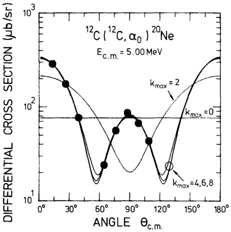
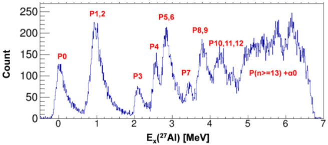



H.W. Becker *et al.*, ZPhys **303** (1981), 305-312

$^{12}$C+$^{16}$O:




X.Fang *et al.*, PRC **96** (2017), 045804

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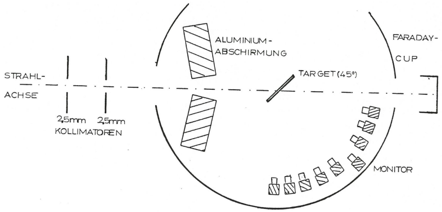


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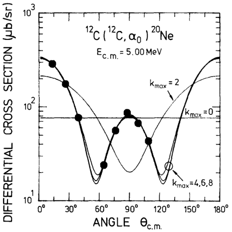
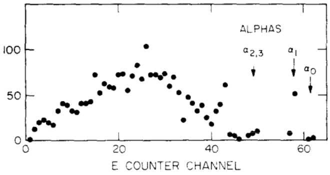


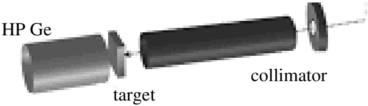

H.W. Becker *et al.*, ZPhys **303** (1981), 305-312

$^{16}$O+$^{16}$O:



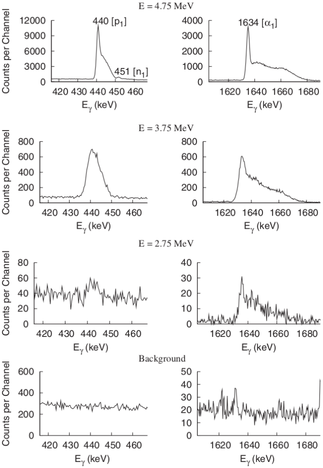

H. Spinka and H. Winkler, NPA **233** (1974), 456–494

# Gamma measurements by Spillane *et al.*




- $E_{\mathrm{c.m.}} = 2.1 - 4.8$ MeV
- $I = 40$ p$\mu$A
- 1 mm thick graphite target
  subtraction of yields
- resolution granularity (HP Ge)
- close $2\pi$ geometry
- normalised to Becker *et al.*
- resonance at $E_{\mathrm{c.m.}} = 2.14$ MeV

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




T. Spillane *et al.*, PRL **98** (2007), 122501

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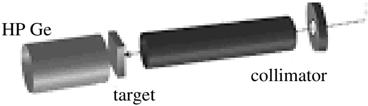


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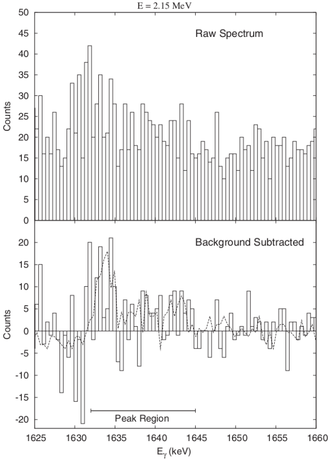
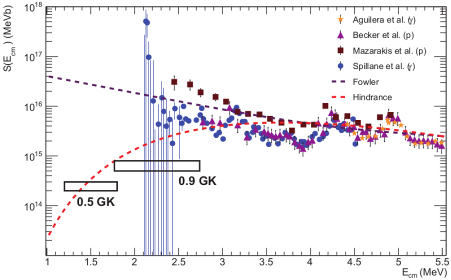



T. Spillane *et al.*, PRL **98** (2007), 122501

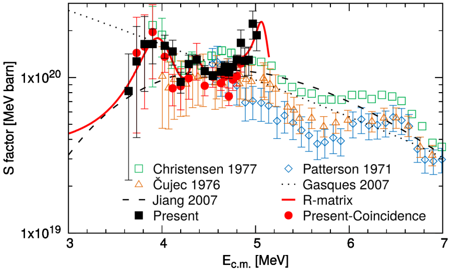
# Conventional measurements: $^{12}C+^{12}C$ state of the art




G. Fruet, PhD thesis (2018)

- particle or gamma measurements
- accelerator calibration
- normalisation: target thickness
- oscillating structure
- uncertainties in astrophysics region of interest
- extrapolations

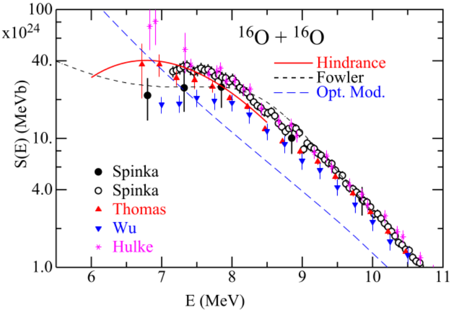
# Conventional measurements: $^{12}C+^{16}O$ state of the art




X. Fang *et al.*, PRC **96** (2017), 045804

- particle or gamma measurements
- overlapping states (+ two-particle decay channels)
- many-body decays
- ? *S*-factor maximum

# Conventional measurements: $^{16}O+^{16}O$ state of the art




C.L. Jiang *et al.*, EPJ A **57** (2021), 235

- particle or gamma measurements
- overlapping states (+ three-particle decay channels)
- statistical models
- normalisation: (oxide or implantation) targets

?? *S*-factor maximum

# Coincidence experiments capable of low-count acquisition runs

- strong fluctuations of the excitation function
  - → increase of reaction rate
  - extrapolations uncertain
  - experimental resolution needed
- possible fusion hindrance with broad maximum
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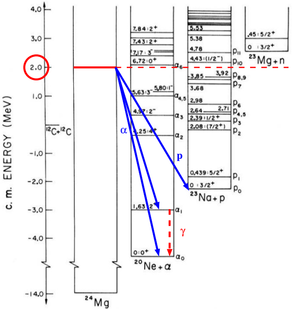
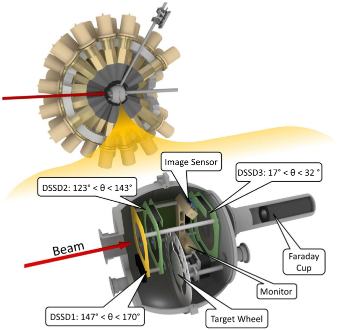



→ gamma-particle coincidences

# Gamma Particle measurements with Gammasphere at ATLAS (ANL)



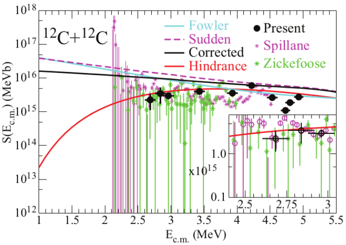

- largely improved uncertainty
- hindrance parameterisation:

  $S$-factor max.: $E_{\mathrm{c.m.}} = 3.5 - 4.0$ MeV

- $I = 1$ p$\mu$A
- thin self supporting target foil
- $4\pi$ Ge detector array:

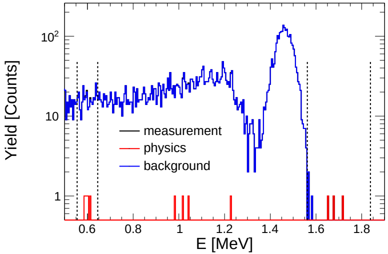
  $\epsilon(440\,\mathrm{keV}) = 9\%$, $\epsilon(1635\,\mathrm{keV}) = 7\%$

- alphas and protons in close geometry




C.L. Jiang *et al.*, PRC **97** (2018), 012801(R)

# Background dominated data acquisition rates



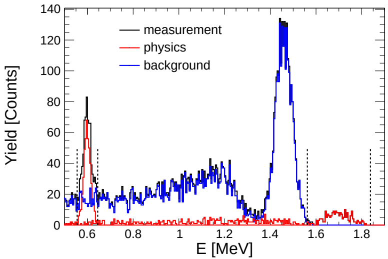

- $n$ : measurement
- $\mu$: physics
- $b$: background
- $R_\gamma, R_\mathrm{p}$: acquisition rates

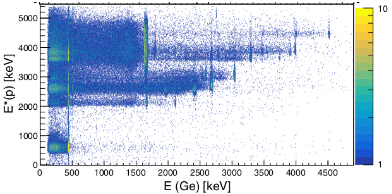
$$b = R_\gamma \cdot R_\mathrm{p} \cdot t_\mathrm{coinc} \cdot t_\mathrm{acqu}$$
$$\mu = n - b$$

- determination of rates in gamma and particle detectors independently

  C.L. Jiang *et al.*, PRC **97** (2018), 012801(R)

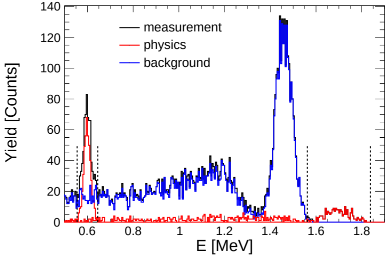
# “Conventional” background estimation

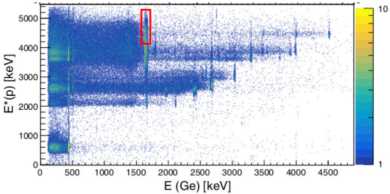



- estimate background (linear, exponential) just outside energy selection gates
- generalise for 2D spectra
- W.P. Tan *et al.*, PRL **124** (2020), 192702

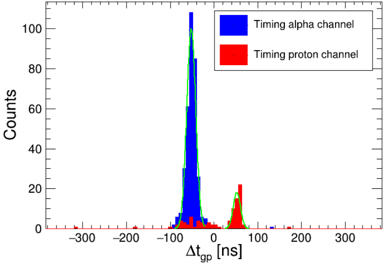
# “Conventional” background estimation



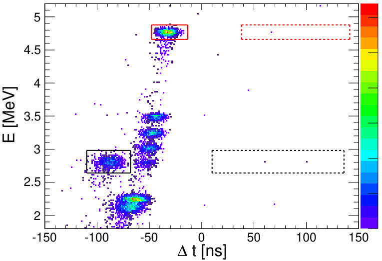




- estimate background (linear, exponential) just outside energy selection gates
- generalise for 2D spectra
- W.P. Tan *et al.*, PRL **124** (2020), 192702

# Fast timing background estimation




J. Nippert *et al.*, submitted to PRC

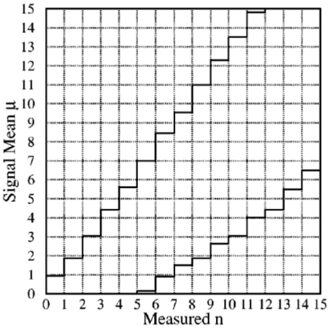



M. Heine *et al.*, EPJ Web Conf **260** (2022), 01004

- identical energy gates for gammas and particles
- select background in non coincident timing domain
- $\sim$ 10 ns gamma-particle timing gates
- G. Fruet *et al.*, PRL **124** (2020), 192701

# Statistical significance in low count-rate measurements

- estimate confidence interval of a signal $\mu$ in a measurement $n$ with background $b$
  $\mu = n - b$
- avoid negative signals (nonphysical)
- limits and asymmetric error bars

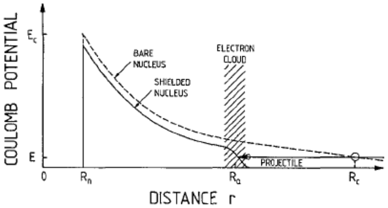



G.J. Feldman and R.D. Cousins *et al.*, PRD **57** (1998), 3873

| $n$ | $b$ | $\mu$ | $\Delta\mu$ | $\Delta\mu_{FC}$ |
|---|---|---|---|---|
| 15 | 12 | 3 | $\sqrt{27}$ | [0, 6.32] |
| 1 | 1 | 0 | $\sqrt{2}$ | [0, 1.75] |
| 2 | 2 | 0 | $\sqrt{4}$ | [0, 2.25] |

# Cross-section enhancement in direct measurements

shielding potential between target atoms and partially ionised beam




H.J. Assenbaum *et al.*, Z. Phys. A **327** (1987) 461

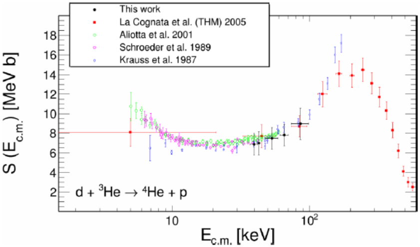
$$U_e = Z_1 Z_2 e^2 / R_a$$
$$E_{eff} = E_{beam} + U_e$$
$$\hookrightarrow E_{eff}/E_{beam}$$

- effect more pronounced for heavier systems ($\alpha+{}^{12}$C, $^{12}$C+$^{12}$C)
- experimental relative energies lower in light systems ($d+d, d+{}^{3}$He)
- discussion about interpretation of data with light systems:

F.C. Barker, Nuc. Phys. A **707** (2002) 277
G. Fiorentini *et al.*, Z. Phys A **350** (1995) 289–301

# Laser Plasma Induced $^3He(d,p)^4He$

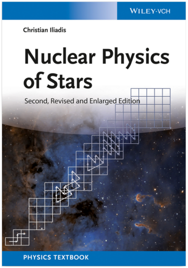
- mixture of $^3He$ and d heated by laser pulses
- d+$^3He$ undergo 'Coulomb explosion' in hot plasma

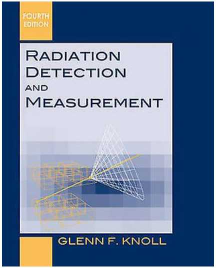


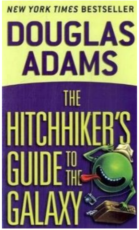

D. Lattuada *et al.*, PRC **93** 045808 (2016) 045808

- measurement non biased by electron screening
- improve error bars:
  1. more precise measurement of the ion energy distribution
  2. higher accuracy with particle yields

# Suggested readings




C. Illiadis: Nuclear Physics of Stars
G.F. Knoll: Radiation Detection and Measurement

D. Adams: The Hitchhiker's Guide to the Galaxy