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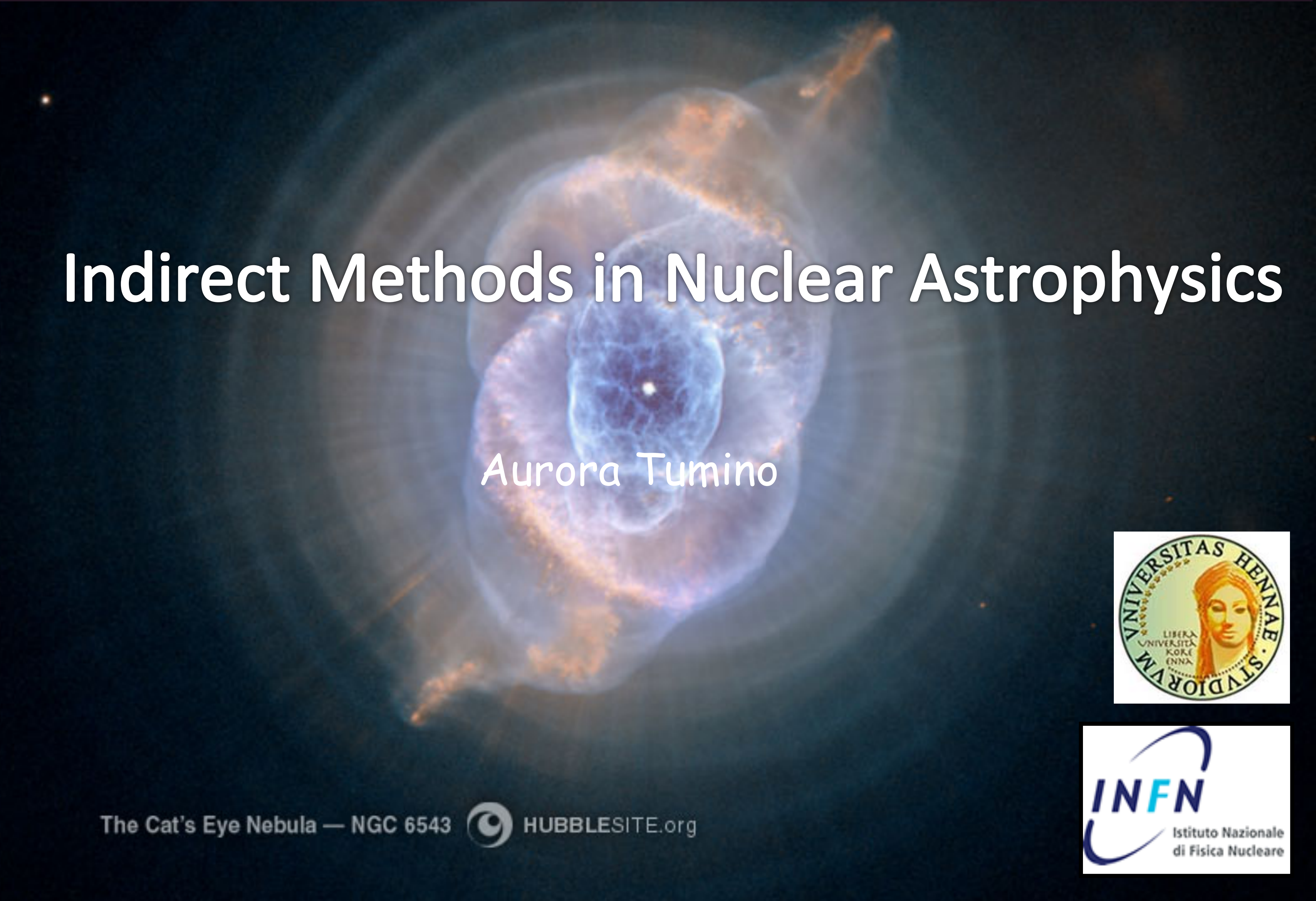

Indirect Methods in Nuclear Astrophysics

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The Cat's Eye Nebula — NGC 6543 HUBBLESITE.org

Outline

- Why do we need indirect techniques in Nuclear Astrophysics?
- Coulomb Dissociation (CD)
- Asymptotic Normalization Coefficients (ANC)
- Trojan Horse Method (THM)
- Physics case: $^{12}C+^{12}C$ fusion at astrophysical energies via the THM

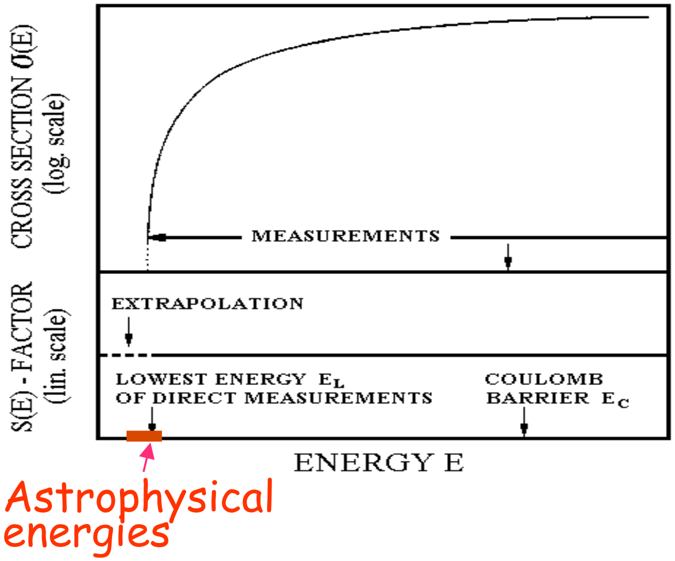
Charged particle cross section measurements at astrophysical energies

σ ~picobarn ⇒ Low signal-to-noise ratio due to the Coulomb barrier between the interacting nuclei

Extrapolation from the higher energies by using the

ASTROPHYSICAL FACTOR

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



S(E) is a smoothly varying function of the energy than the cross section σ(E)

…but large uncertainties in the extrapolation

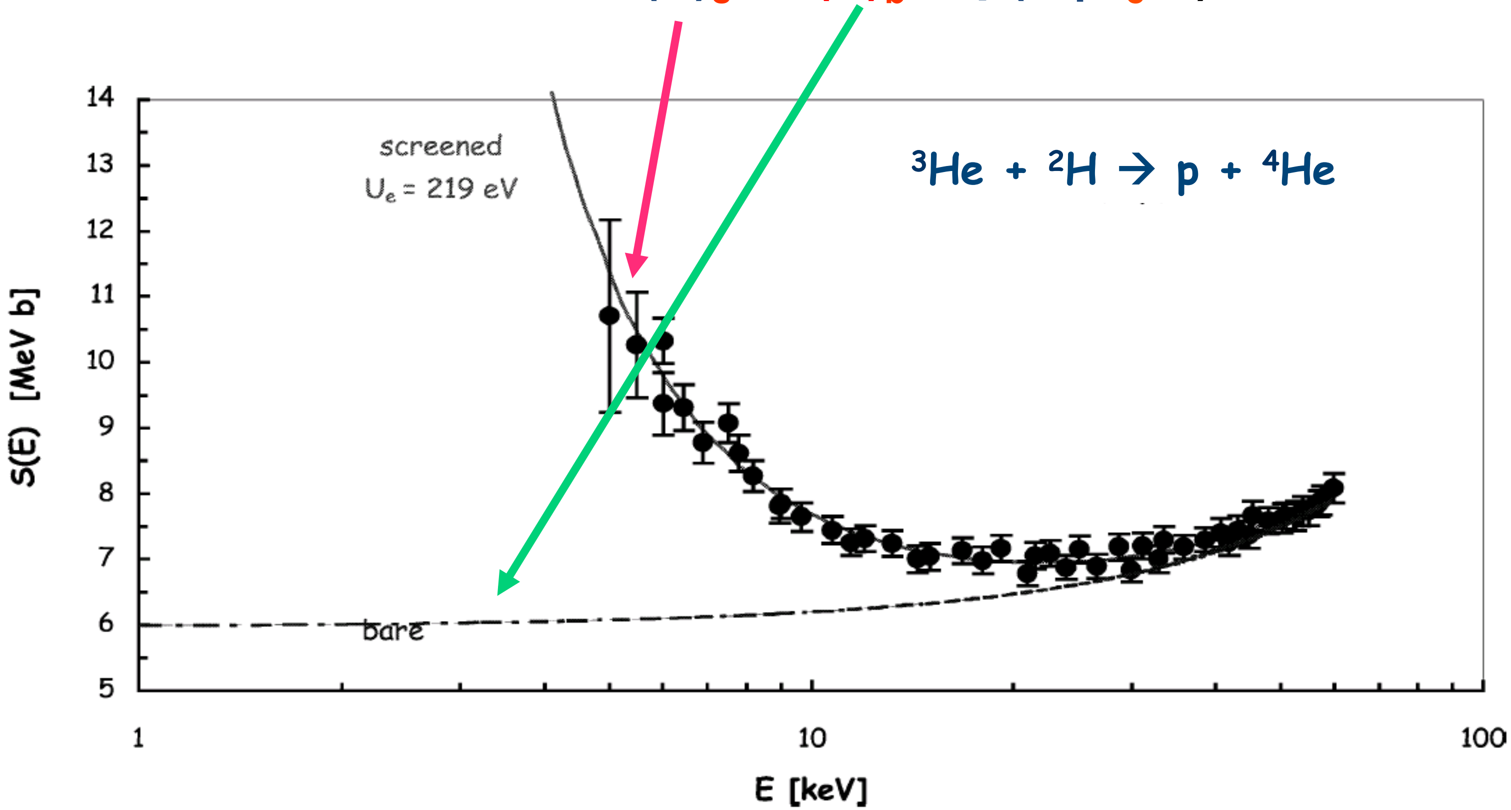
→ experimental improvements/solutions to measure at low energies

...but... further problem at astrophysical energies → → → →

Electron Screening

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

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



$S(E)_b$ needed to assess the reaction rate, BUT no way to measure $S(E)_b$ directly

Indirect Methods for Nuclear Astrophysics

Quite straightforward experiment, no Coulomb suppression, no electron screening but …

Entrance channel
A+a → Several reaction mechanisms link the two channels → Reaction products
C+c+…

The reaction theory is needed to select only one reaction mechanism. However, nowadays powerful techniques and observables for careful data analysis and theoretical investigation.

For review see:
R. Tribble et al., Rep. Prog. Phys. ***77*** (2014) 106901

-> -> -> INDIRECT METHODS

- **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)**

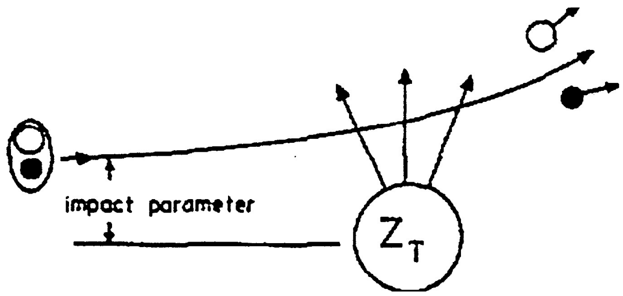
  … to determine the S(0) factor of the radiative capture reaction, **A+x → B+γ** studying a peripheral transfer reaction into a bound state of the B nucleus

- **Trojan Horse Method (THM)**

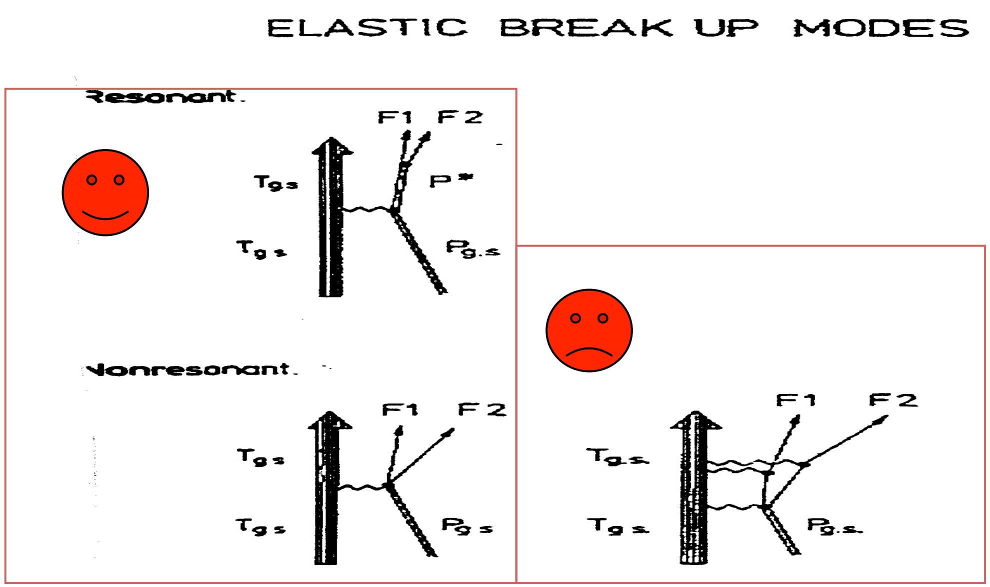
  …to determine the S(E) factor of a charged particle reaction **A+x→c+C** selecting the Quasi Free contribution of an appropriate **A+a(x+s)→ c+C+s** reaction

Coulomb dissociation

• If we send a projectile B with high velocity through the Coulomb field of an high Z target (for ex. ^{208}Pb) strong electromagnetic fields are present for a short time. This variable electromagnetic field is equivalent to a photon flux which can lead to the photodisintegration of B.



• We are interested in studying 3-body reactions that can be sketched in the following way:



From Coulomb dissociation to photoabsorption

The cross-section for Coulomb dissociation (C.D.) can be linked to the photoabsorption one by the following expression:

$$\frac{d^2\sigma}{dE\,d\Omega_{aA}} = \frac{1}{E_\gamma}\sum_\lambda \sigma_{E\lambda}(a+\gamma \to b+x)\frac{dn_{E\lambda}}{d\Omega_{Aa}}$$

From photoabsorption to radiative capture

$$\sigma_{E\lambda}(b+x \to a+\gamma) = \frac{2(2J_a+1)}{(2J_b+1)(2J_x+1)}\frac{k_\gamma^2}{k_{bx}^2}\sigma_{E\lambda}(a+\gamma \to b+x)$$

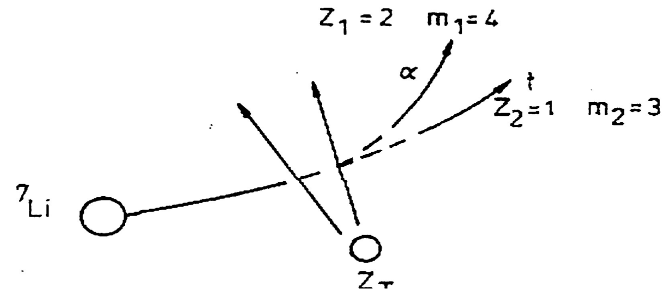
Some important considerations:

C.D. enhances the number of events with respect to the ones for the original capture process, by a large factor. This is due to:
- large virtual photon number,
- possibility to use thick targets,
- phase space factor $(k_x/k_\gamma)^2$ from detailed balance linking σ_{photo} with σ_{capt}.

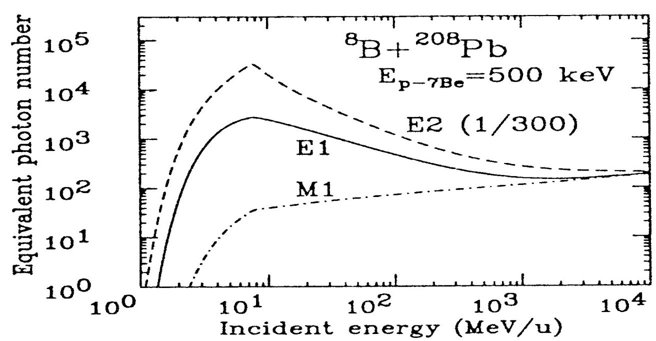
Contrary to a photodissociation reaction, fragments emerge with high velocity making their detection easier.

The nuclear contribution to the break-up must be negligible → large impact parameters → small fragment detection angles needed. Otherwise quantal calculations (DWBA/Eikonal), optical potentials needed

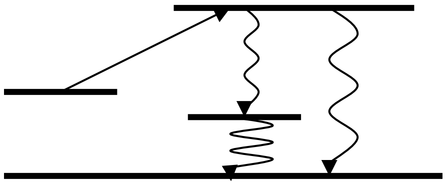
Post acceleration effects must be negligible → high projectile velocities decrease their effects. Otherwise higher-order effect of Coulomb interaction accounted for with various theoretical approaches such as:
Time-dependent dynamical calculations



One has to take properly into account that different multipolarities can contribute with different weights in the dissociation processes and radiative capture processes. Effects on angular distributions,
on the slope of the extracted S factor.



C.D. provides only information on the radiative capture to the ground state.



The $^7Be(p,\gamma)^8B$ case

The $^7Be(p,\gamma)^8B$ reaction is connected with the Solar Neutrino problem. Studied by different groups.

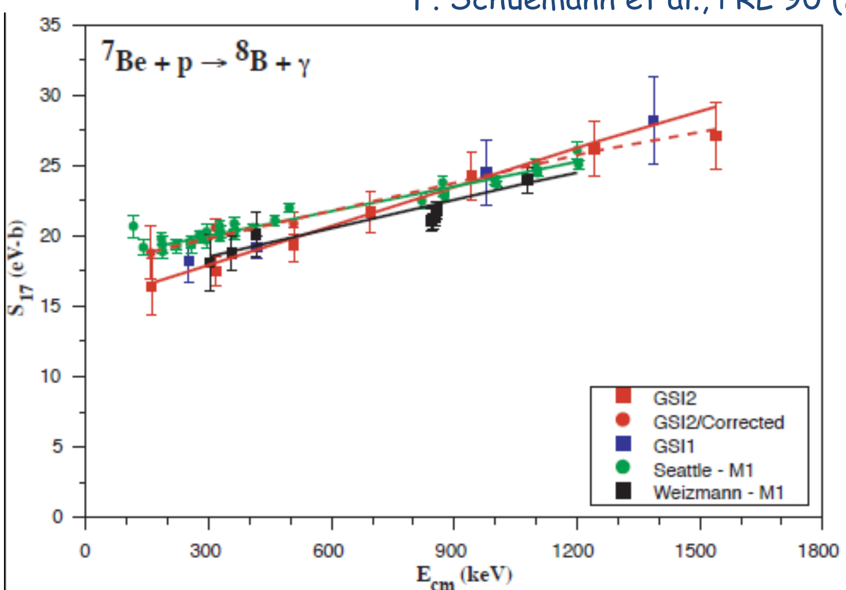
GSI experiments 2003: Significant contribution from E2 multipolarity excluded. $S_{17}(0)=18.1\pm0.3$ eV·b

However, two major differences between CD and direct S(E) factors:

. $S_{17}(0)$ from CD measurements about 10% lower than the mean of direct measurements

. $S_{17}(E)$ slope from CD steeper than from direct measurements

F. Schuemann et al., PRL 90 (2003) 232501



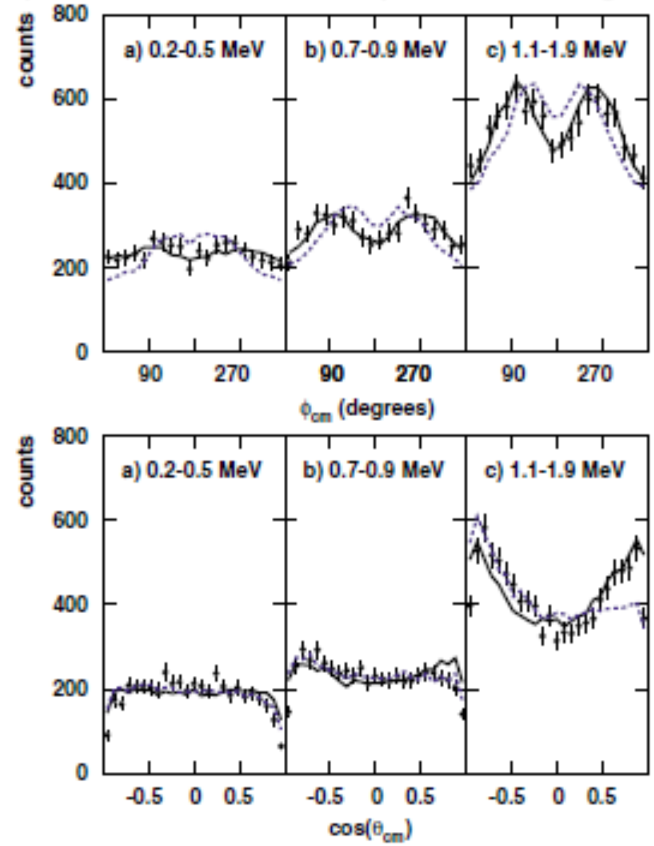


FIG. 3 (color online). Top: Experimental distributions of the proton azimuthal angular (ϕ_{cm}) distributions for three different bins of the p-^{7}Be relative energy, E_{rel}. The full histograms denote a first-order perturbation-theory calculation for $E1$ multipolarity, and the dashed ones for $E1 + E2$. All theoretical curves were individually normalized to the data points in each frame. Bottom: the same for the polar breakup angles, θ_{cm}.

GSI corrected: more accurate Coloumb break-up theory brings to the agreement
(H. Esbensen et al., PRL 94 (2005) 42502)

...alternative analysis via ANC

Some References on C.D.

1)G. Baur et al. J.Phys. G 20,1, (1994)
2)G. Baur et al. Annu. Rev. Nucl. Part. Sci. 46, 321,(1996)
3)T. Motobayashi et al.:NPA 719,65c,2003)
4)J. Kiener et al. PRC 44,2195,(1991)

$^{7}Be(p,\gamma)^{8}B$

5)T.Motobayashi et al.: PRL 73,2680,(1994)
NPA 693,258,(2001)
6)T.Tikuchi et al: PLB 391,261,(1997)
7)T.Tikuchi et al: EPJ A3,213,(1998)
8)B.Davids et al.: PRL 86,2750,(2001)
EPJ A15,65,(2002)
9)F. Schuemann et al., PRL 90 (2003) 232501
10)H. Esbensen et al., PRL 94 (2005) 42502
10) M. Gai et al., PRC 74 (2006) 025810

$^{13}N(p,\gamma)^{14}O$

11)J. Kiener et al.: NPA 552, 66, (1993)
12) Motobayashi et al. PLB 264, 259, (1991)

$^{2}H(\alpha,\gamma)^{6}Li$

13) F. Hammache et al., Phys. Rev. C 82 (2010) 065803
14) J.Kiener et al.: PRC 44,2195,(1991)

$^{14}C(n,\gamma)^{15}C$

H. Esbensen, Phys. Rev. C 80, 024608 (2009)

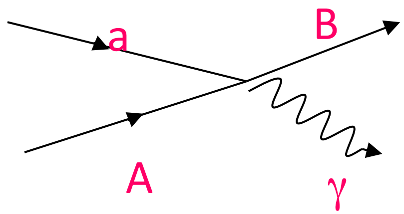
Table 2 Radiative capture reactions of interest for light-element synthesis accessible by of fast projectiles

Reaction	$T_{1/2}$ (projectile)	Astrophysical application
$^{3}He(\alpha,\gamma)^{7}Be$	53.3 days	Solar-neutrino problem
$^{7}Be(p,\gamma)^{8}B$	770 ms	^{3}He abundance
$^{7}Be(\alpha,\gamma)^{11}C$	20.4 min	
$^{4}He(d,\gamma)^{6}Li$	Stable	Primordial nucleosynthesis of Li Be B-isotopes
$^{6}Li(p,\gamma)^{7}Be$	53.3 days	
$^{6}Li(\alpha,\gamma)^{10}B$	Stable	
$^{4}He(t,\gamma)^{7}Li$	Stable	
$^{7}Li(\alpha,\gamma)^{11}B$	Stable	
$^{11}B(p,\gamma)^{12}C$	Stable	
$^{9}Be(p,\gamma)^{10}B$	Stable	
$^{10}B(p,\gamma)^{11}C$	20.4 min	
$^{7}Li(n,\gamma)^{8}Li$	842 ms	Primordial nucleosynthesis in inhomogeneous B
$^{8}Li(n,\gamma)^{9}Li$	178 ms	
$^{12}C(n,\gamma)^{13}C$	Stable	
$^{14}C(n,\gamma)^{15}C$	2.45 s	
$^{14}C(\alpha,\gamma)^{18}O$	Stable	
$^{12}C(p,\gamma)^{13}N$	10 min	CNO cycles
$^{16}O(p,\gamma)^{17}F$	65 s	
$^{13}N(p,\gamma)^{14}O$	70.6 s	
$^{20}Ne(p,\gamma)^{21}Na$	22.5 s	
$^{11}C(p,\gamma)^{12}N$	11ms	Hot *p-p* chain
$^{15}O(\alpha,\gamma)^{19}Ne$	17.2 s	rp process
$^{31}S(p,\gamma)^{32}Cl$	291 ms	
$^{12}C(\alpha,\gamma)^{16}O$	Stable	Helium burning
$^{16}O(\alpha,\gamma)^{20}Ne$	Stable	
$^{14}N(\alpha,\gamma)^{18}F$	109.7 min	

Asymptotic Normalization Coefficients

At low relative energies the S(0) for a (peripheral) direct capture reaction a+A → B+γ

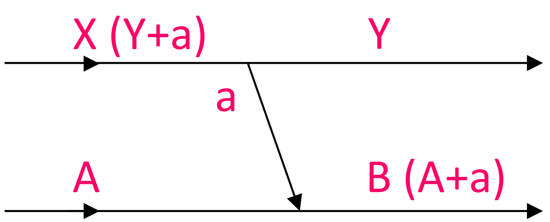
$$S(0)_{DC} \propto (C^{B}_{aA})^2$$



C^{B}_{aA} is the so called ANC that specifies the tail of the B overlap function in the a+A channel

For a peripheral transfer reaction X+A → Y+B into a bound state of B,

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} \propto (C^{B}_{aA})^2 \cdot (C^{X}_{Ya})^2 \left(\frac{d\tilde{\sigma}}{d\Omega}\right)_{DW}$$



reduced DWBA cross section insensitive to the bound state potential parameters

The ANC C^{B}_{aA} can be obtained normalising the calculated angular distribution to the experimental one. What we need: precise optical potentials and one additional ANC (from elastic scattering angular distributions)

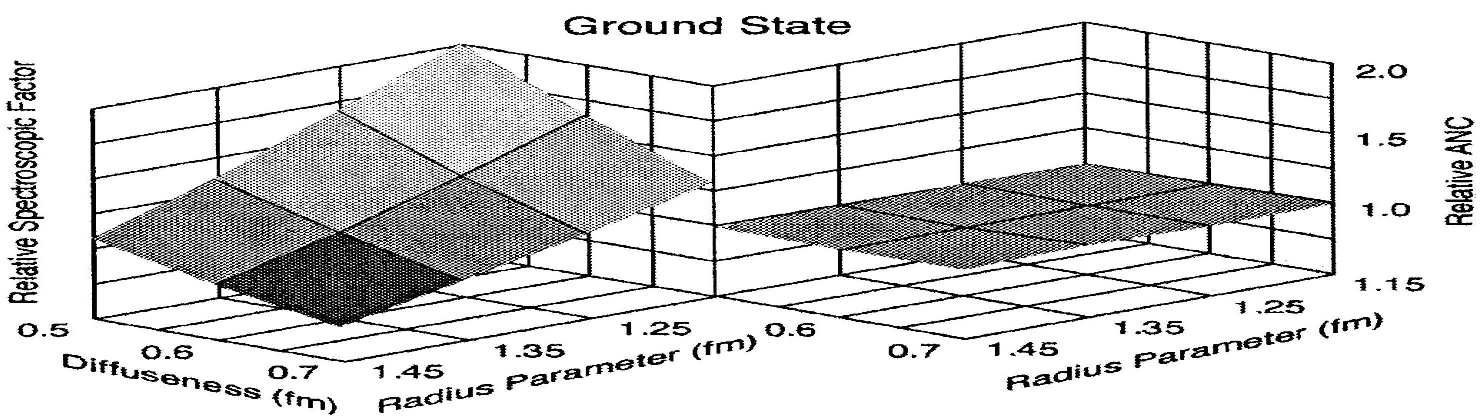
Uncertainties on Spectroscopic factors and ANC

The spectroscopic factor in conventional DWBA analysis is linked to the properties of nuclear interior and its value depends upon the parameters chosen for the bound state potential in the calculations.

The ANC in DWBA analysis of peripheral transfer reactions is less sensitive upon the parameters used for the bound state wave function.

Example

Relative variation of spectroscopic factor and ANC for the g.s. of ^{15}O as obtained from DWBA analysis of $^{14}N(^{3}He,d)^{15}O_{g.s.}$
(F.P.Bertone et al.:PRC66,055804,(2002))



The $^7Be(p,\gamma)^8B$ case

Ref: A. Azahari et al. Phys.Rev.C63, 055803(2001)

ANC for ^8B, $C_{p^7Be}^{^8B}$ were extracted for two transfer reactions:

$^{10}B(^7Be,^8B)^9Be$ and $^{14}N(^7Be,^8B)^{13}C$

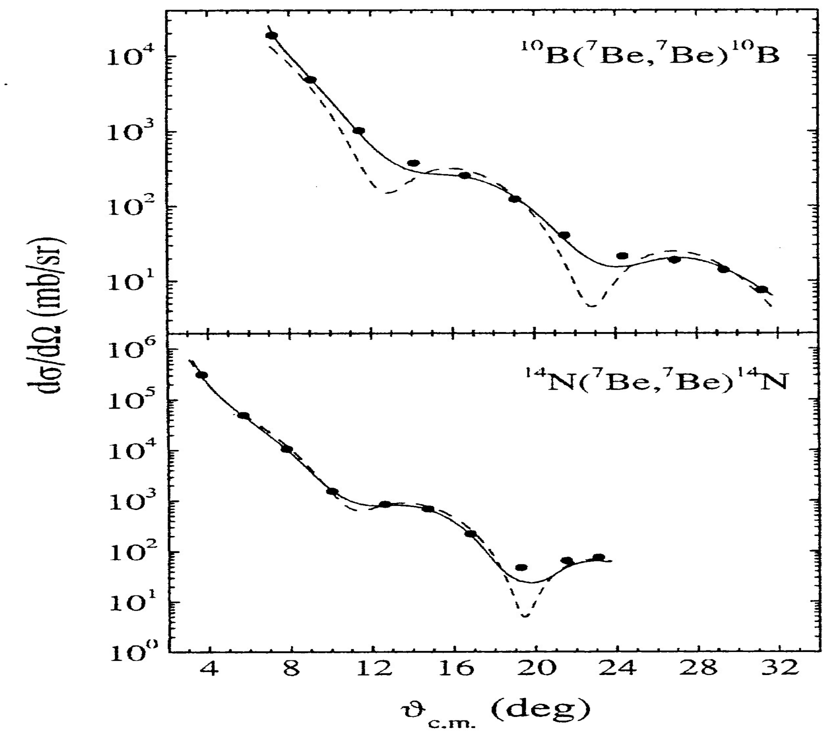
Experiment

$E(^7Be)$=85MeV $\Delta E/E$=1.9% i=5•10^4 pps

Reaction products detected and identified by two DE(100mm) E(1000mm) position sensitive Si telescopes on both sides of the beam.

Elastic angular distributions

Appropriate optical model potentials to reproduce elastic scattering.



- - - - Calculated angular distributions

—— Same angular distributions corrected for finite angular resolution

Stability of the results

ANC dependence on the Optical Model potentials: the authors quote an uncertainty <10% due to Optical Model potentials.

The ANC were used to calculate $S_{17}(0)$ obtaining:

$S_{17}(0)$=18.4±2.5 eV·b from $^{10}B\ (^{7}Be,^{8}B)^{9}Be$

$S_{17}(0)$=16.9±1.9 eV·b from $^{14}N\ (^{7}Be,^{8}B)^{13}C$

Averaging the C^{8B} values obtained in the two transfer reactions one obtains:
$S_{17}(0)$=17.3±1.8 eV·b

Some References on ANC

1)A.M. Mukhamedzhanov et al.: PRC 56,1302,(1997)
2)H.M.Xu et al :PRL 73,2027,(1994)
3)C.A.Gagliardi et al: EPJ A15,69,(2002)

• $^{7}Be(p,\gamma)^{8}B$ via $^{10}B(^{7}Be,^{8}B)^{9}Be$ and $^{14}N(^{7}Be,^{8}B)^{13}C$
4)A.Azhari et al: PRC 63,055803,(2001)

• $^{16}O(p,\gamma)^{17}F$ via the $^{16}O(^{3}He,d)^{17}F$ transfer reaction
5)C.A.Gagliardi et al.: PRC 59,1149,(1999)

• $^{14}N(p,\gamma)^{15}O$ via the $^{14}N(^{3}He,d)^{15}O$ transfer reaction
5) F.P.Bertone et al.:PRC66,055804,(2002)

• $^{12}C(n,\gamma)^{13}C$ via the $^{12}C(d,p)^{13}C$ transfer reaction
6)N.Imai et al.:NPA, 688,281,(2001)

• $^{15}N(p,\gamma)^{16}O$ via the $^{15}N(^{3}He,d)^{16}O$ transfer reaction
7) A.M. Mukhamedzhanov et al., J. Phys.: Conf. Ser. 202 012017 (2010)

• $^{12}C(n,\gamma)^{13}C$ via $^{13}C(^{12}C,^{13}C)^{12}C$
8) Al. Abdullah et al., PRC 81 035802 (2010)

• $^{13}C(\alpha,n)^{16}O$ via $^{6}Li(^{13}C,d)^{17}O$
9)M. L. Avila, et al., PRC 91, 048801 (2015)

Trojan Horse Method

Basic principle: astrophysically relevant two-body σ from quasi- free contribution of an appropriate three-body reaction

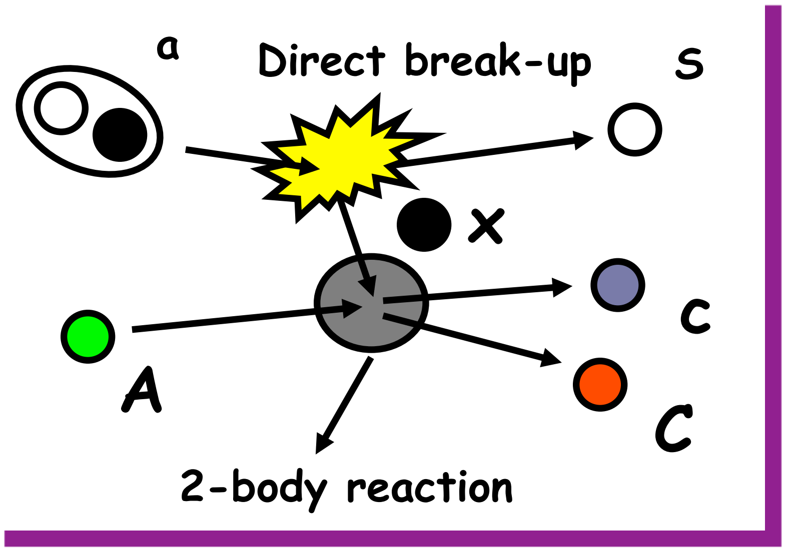
$$A + a \rightarrow c + C + s \quad \rightarrow\rightarrow\rightarrow \quad A + x \rightarrow c + C$$

a: x ⊕ s clusters

Quasi-free mechanism

✓ only x - A interaction

✓ s = spectator (p_s~0)



$E_A > E_{Coul} \Rightarrow$ NO Coulomb suppression

NO electron screening

$E_{q.f.} = E_{Ax} - B_{x\text{-}s}$ ± intercluster motion

plays a key role in compensating for the beam energy

→ $E_{q.f.} \approx 0$!!!

Theoretical approaches to the THM

$A + a \rightarrow c + C + s \rightarrow \rightarrow \rightarrow A + x \rightarrow c + C$

PWIA hypotheses:

- beam energy > $a = x \oplus s$ breakup Q-value
- projectile wavelength $k^{-1} \ll x - s$ intercluster distance

$$\frac{d^3\sigma}{d\Omega_c d\Omega_C dE_c} = C \cdot KF \cdot |\varphi(p_s)|^2 \frac{d\sigma^N}{d\Omega}$$

MPWBA formalism

(*S. Typel and H. Wolter, Few-Body Syst. 29 (2000) 75*)

- distortions introduced in the c+C channel, but plane waves for the three-body entrance/exit channel

- off-energy-shell effects corresponding to the suppression of the Coulomb barrier are included

but **No absolute value of the cross section**

KF kinematical factors

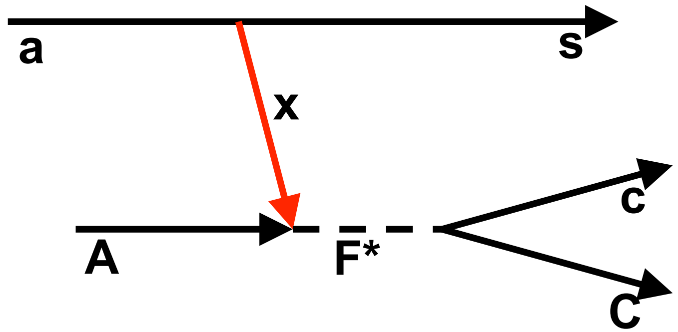
$|\phi|^2$ **momentum distribution of** ***s*** **inside** ***a***

$d\sigma^N/d\Omega$ **Nuclear cross section for the** $A+x \rightarrow C+c$ **reaction**

A. Tumino et al., PRL 98, 252502 (2007)

...for resonant reactions

The A + a(x+s) → F*(c + C) + s process is a transfer to the continuum where particle x is the transferred particle



Standard R-Matrix approach cannot be applied to extract the resonance parameters → Modified R-Matrix is introduced instead

In the case of a resonant THM reaction the cross section takes the form

$$\frac{d^2\sigma}{dE_{Cc}\,d\Omega_s} \propto \frac{\Gamma_{(Cc)_i}(E)\,|M_i(E)|^2}{(E - E_{R_i})^2 + \Gamma_i^2(E)/4}$$

$M_i(E)$ is the amplitude of the transfer reaction (upper vertex) that can be easily calculated → The resonance parameters can be extracted

Advantages:

- possibility to measure down to zero energy
- No electron screening
- HOES reduced widths are the same entering the OES S(E) factor (New!)

What has to be done practically?

Before data taking

1) Choice of a suitable Trojan Horse nucleus, e.g. ^6Li (a-d structure with $E_{binding}$=1.47MeV), d (p-n structure with $E_{binding}$ =2.22MeV)
2) Choice of suitable kinematical conditions which correspond to the expected quasi free contribution

After data taking

3) Selection of the three body reaction of interest.

4) Check if the quasi free reaction mechanism is present and can be discriminated from others.

5) Reconstruct σ^{2b}_{bare} and multiply it by the penetration factor.

6) Normalise σ^{2b}_{THM} to σ^{2b}_{Direct} at higher energies, where available.

7) Verify agreement with direct data in the overlapping region
   - excitation functions including resonances
   - angular distributions

8) If points 1-7 are true, we believe that THM data are reliable where direct data are not available.

	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	
1	$^{7}Li(p, \alpha)^{4}He$	$^{2}H(^{7}Li, \alpha\,\alpha)n$	19-22	15.122	TANDEM 13 MV LNS-INFN, Catania	Spitaleri *et al.* PRC,1999, Lattuada *et al.* ApJ, 2001
2	$^{7}Li(p, \alpha)^{4}He$	$^{7}Li(^{3}He, \alpha\,\alpha)d$	33	11.853	CYCLOTRON, Rez, Praha	Tumino *et al.* EPJ, 2006
3	$^{6}Li(p, \alpha)^{3}He$	$^{2}H(^{6}Li, \alpha\,^{3}He)n$	14,25	1.795	TANDEM 13 MV LNS-INFN, Catania	Tumino *et al.* PRC, 2003
4	$^{9}Be(p, \alpha)^{6}Li$	$^{2}H(^{9}Be, \alpha\,^{6}Li)n$	22	-0.099	TANDEM CIAE, Beijing TANDEM 13 MV LNS-INFN, Catania	Wen *et al.* PRC, 2008, Wen et al. JPG 2011
5	$^{11}B(p, \alpha)^{8}Be$	$^{2}H(^{11}B, \alpha\,^{8}Be)n$	27	6.36	TANDEM 13 MV LNS-INFN, Catania	Spitaleri *et al.* PRC, 2004, Lamia *et al.* JPG, 2011
6	$^{15}N(p, \alpha)^{12}C$	$^{2}H(^{15}N, \alpha\,^{12}C)n$	60	2.74	CYCLOTRON, TAMU, College Station TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* PRC, 2008
7	$^{18}O(p, \alpha)^{15}N$	$^{2}H(^{18}O, \alpha\,^{15}N)n$	54	1.76	(CYCLOTRON, TAMU, College Station TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* PRL 2008,
8	$^{19}F(p, \alpha)^{16}O$	$^{2}H(^{19}F, \alpha\,^{16}O)n$	50,55	8.11	TANDEM 13 MV LNS-INFN, Catania	La Cognata *et al.* ApJ Lett., 2011 Indelicato et al. ApJ 2017
9	$^{17}O(p, \alpha)^{14}N$	$^{2}H(^{17}O, \alpha^{14}N)n$	45	-1.032	TANDEM 13 MV LNS-INFN, Catania TANDEM 11 MV Notre Dame	Sergi et al. PRC (R), 2010 Sergi et al PRC 2016

	Binary reaction	Indirect reaction	E_{lab}	Q_3	Accelerator	Ref.
10	$^{18}F(p,\alpha)^{15}O$	$^{2}H(^{18}F,\alpha^{15}O)n$	48	0.65	CYCLOTRON CNS-RIKEN, Tokyo	Cherubini et al. PRC 2015 Pizzone et al. EPJ 2016
11	$^{10}B(p,\alpha)^{7}Be$	$^{2}H(^{10}B,\alpha^{7}Be)n$	27	-1.078	TANDEM 13 MV LNS-INFN, Catania	Spitaleri et al. PRC 2014 Spitaleri et al. PRC 2017
12	$^{6}Li(d,\alpha)^{4}He$	$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$	5 4.8	20.9	TANDEM Demoscritos,Atene TANDEM, IRB, Zagreb	Cherubini *et al.* ApJ, 1996 Spitaleri *et al* .PRC, 2001
13	$^{6}Li(d,\alpha)^{4}He$	$^{6}Li(^{6}Li,\alpha\alpha)^{4}He$	6	20.9	CYCLOTRON Rez, Praha	Pizzone et al. PRC, 2011
14	$^{3}He(d,\alpha)^{1}H$	$^{6}Li(^{3}He,p^{4}He)^{4}He$	5,6	16.878	DINAMITRON, Bochum	La Cognata *et al.* 2005
15	$^{2}H(d,p)^{3}H$	$^{2}H(^{6}Li,p^{3}He)^{4}He$	14	2.59	DINAMITRON, Bochum	Rinollo *et al.* EPJ 2005
16	$^{2}H(d,p)^{3}H$	$^{2}H(^{3}He,p^{3}H)^{1}H$	18	-1.46	CYCLOTRON, Rez, Praha	Tumino et al. PLB 2011 Tumino et al. APJ 2014
17	$^{2}H(d,n)^{3}He$	$^{2}H(^{3}He,n^{3}He)^{1}H$	18	-2.224	CYCLOTRON Rez, Praha	Tumino et al. PLB 2011 Tumino et al. APJ 2014
18	$^{9}Be(p,d)^{8}Be$	$^{9}Be(d,d^{8}Be)n$	18	-1.66	TANDEM 13 MV CIAE, Beijing	Qungang Wen et al.2016
19	$^{6}Li(n,a)^{3}H$	$^{2}H(^{6}Li,t\,\alpha)^{1}H$	14	2.224	TANDEM 13 MV LNS-INFN, Catania	Tumino et al.,EPJ A 2005 Gulino et al., JPG 2010

	Binary reaction	Indirect reaction	E_{lab}	Q	Accelerator	Ref.
20	$^{17}O(n,a)^{14}C$	$^{17}O(n, a^{14}C)^{1}H$	43.5	-0.40 7	TANDEM 11 MV Notre Dame TANDEM 13 MV LNS-INFN, Catania	Gulino et al. PRC(R) 2013
21	$^{13}C(a,n)^{16}O$	$^{13}C(^{6}Li, a\ n)^{16}O$	7.82	3.85	TANDEM FSU, Tallaassee, Florida, USA	La Cognata et al. PRL 2013 La Cognata et al ApJ 2013
22	$^{12}C(^{12}C,a)^{20}Ne$ $^{12}C(^{12}C,p)^{23}Na$	$^{12}C(^{14}N,a^{20}Ne)^{2}H$ $^{12}C(^{14}N,p^{23}Na)^{2}H$	30	-5.65 -8.03	TANDEM 13 MV LNS-INFN, Catania	Tumino et al. Nature 2018
23	$^{12}C(a,a)^{12}C$	$^{13}C(^{6}Li, a\ n)^{16}O$	20	0	TANDEM 13 MV LNS-INFN, Catania	Spitaleri et al. EPJ 2000
24	$^{1}H(p,p)^{1}H$	$^{2}H(p,pp)n$	5,6	2,224	CYCLOTRON ATOMKI,Debrecen TANDEM IRB, Zagreb TANDEM 13 MV LNS-INFN, Catania TANDEM 5 MV Napoli University	Tumino et al. PRL 2007 Tumino et al. PRC 2008
25 0	$^{19}F(a,p)^{22}Ne$	$^{6}Li(^{19}F,p^{22}Ne)^{2}H$	6	1.2	IRB, Zagreb, TANDEM	Pizzone et al. ApJ 2017 D'Agata et al ApJ 2018
25 0	$^{7}Be(n,a)^{4}He$	$^{2}H(^{7}Be,aa)^{1}H$	43.5	16.7	TANDEM LNL- INFN, Catania	L. Lamia et al., to be submitted

12C+12C fusion

Great interest in a wide range of stellar burning scenarios in carbon-rich environments such as late evolutionary stages of stars with more than 8 $M_{\odot}$

superbursts from accreting neutron stars

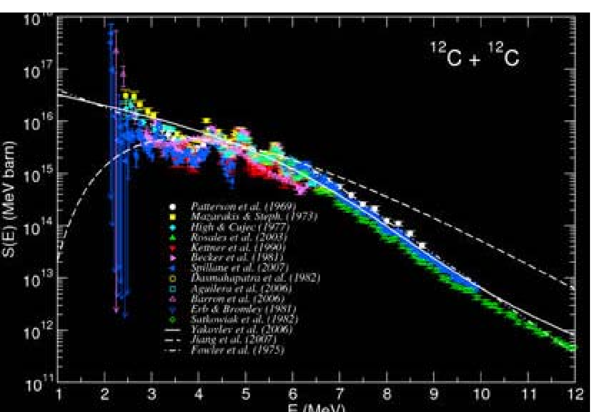
ignition conditions of Sne Ia

Carbon burning temperature from 0.4 to 1.2 GK → E_{cm} from 1 to 2 MeV

Principal reactions:

$^{12}C(^{12}C,\alpha)^{20}Ne$	+ 4.617 MeV	The most frequent results of the interaction
$^{12}C(^{12}C,p)^{23}Na$	+ 2.241 MeV	
$^{12}C(^{12}C,n)^{23}Mg$	- 2.599 MeV	
$^{12}C(^{12}C,\gamma)^{24}Mg$	+13.933 MeV	
$^{12}C(^{12}C,2\alpha)^{20}Ne$	-0.113 MeV	

Considerable efforts to measure the $^{12}C+^{12}C$ cross section at astrophysical energies, but still unknown!!



M.G. Mazarakis & W.E. Stephensen, Phys. Rev. C 7 1280 (1973)
K. U. Kettner *et al.*, Phys. Rev. Lett. 38, 337 (1977)
H.W. Becker et al., Z. Phys. A 303, 305 (1981)
L. Barron-Palos et al., Nucl. Phys. A 779, 318 (2006)
E.F. Aguleira et al.,Phys. Rev. C 73, 064601 (2006)
T. Spillane et al., Phys. Rev. C 73, 064601 (2006)
T. Spillane et al., Phys. Rev. Lett. 98, 122501 (2007)
B. Bucher et al., Phys. Rev. Lett. 114, 251102 (2015)
C.L. Jiang et al., Phys. Rev. C 97 012801 (2018)

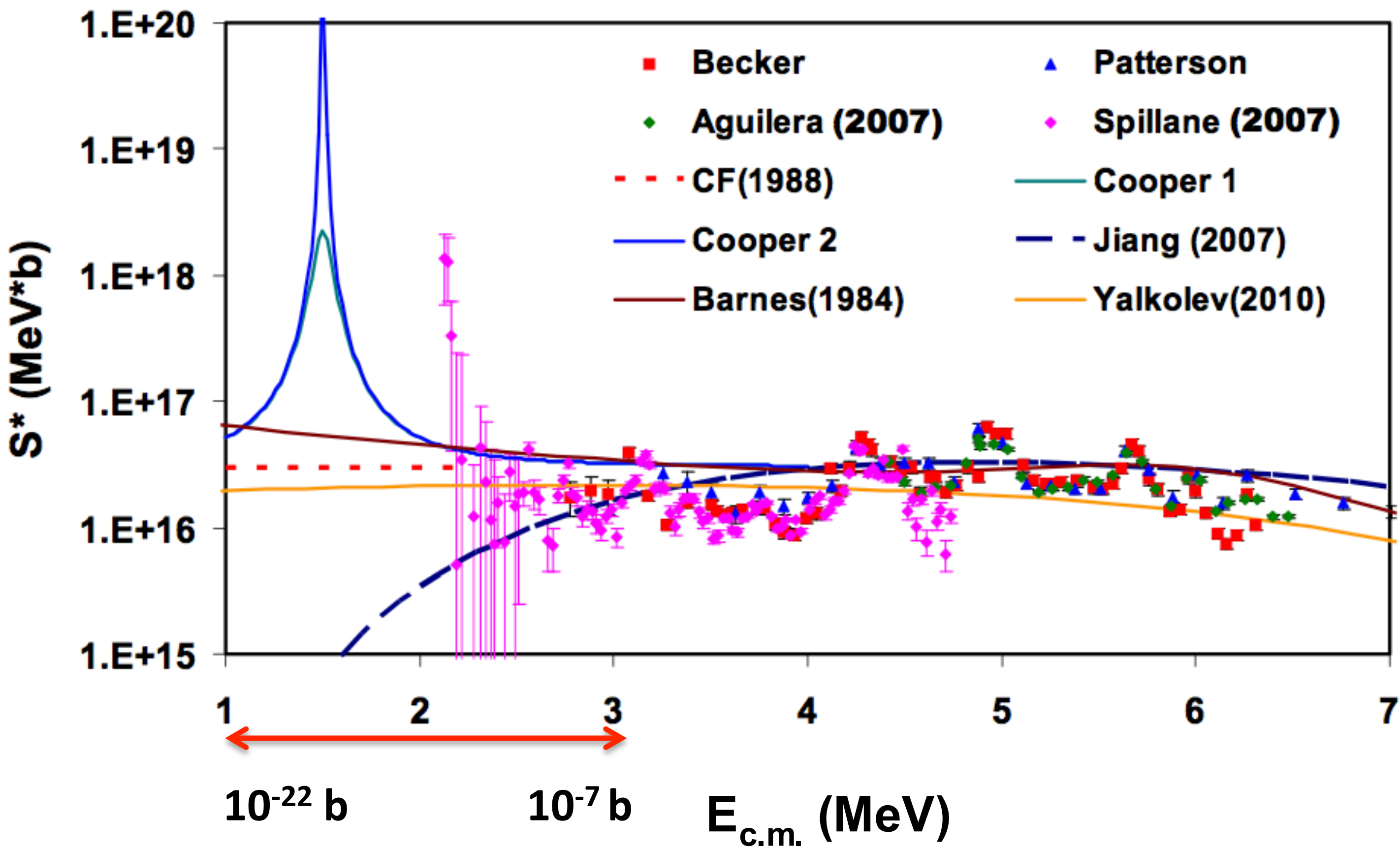
C-burning: State-of-the-art

Resonances at nearly every 300 keV down to E_{cm} = 2.14 MeV. They would increase the present nonresonant reaction rate of the alpha(proton) channel by a factor of 5(2) .

$$S^*(E) = \sigma(E) E \exp\left(\frac{87.21}{\sqrt{E}} + 0.46E\right)$$

extrapolations differ by 3 orders of magnitude

large uncertainties in astrophysical models of stellar evolution and nucleosynthesis



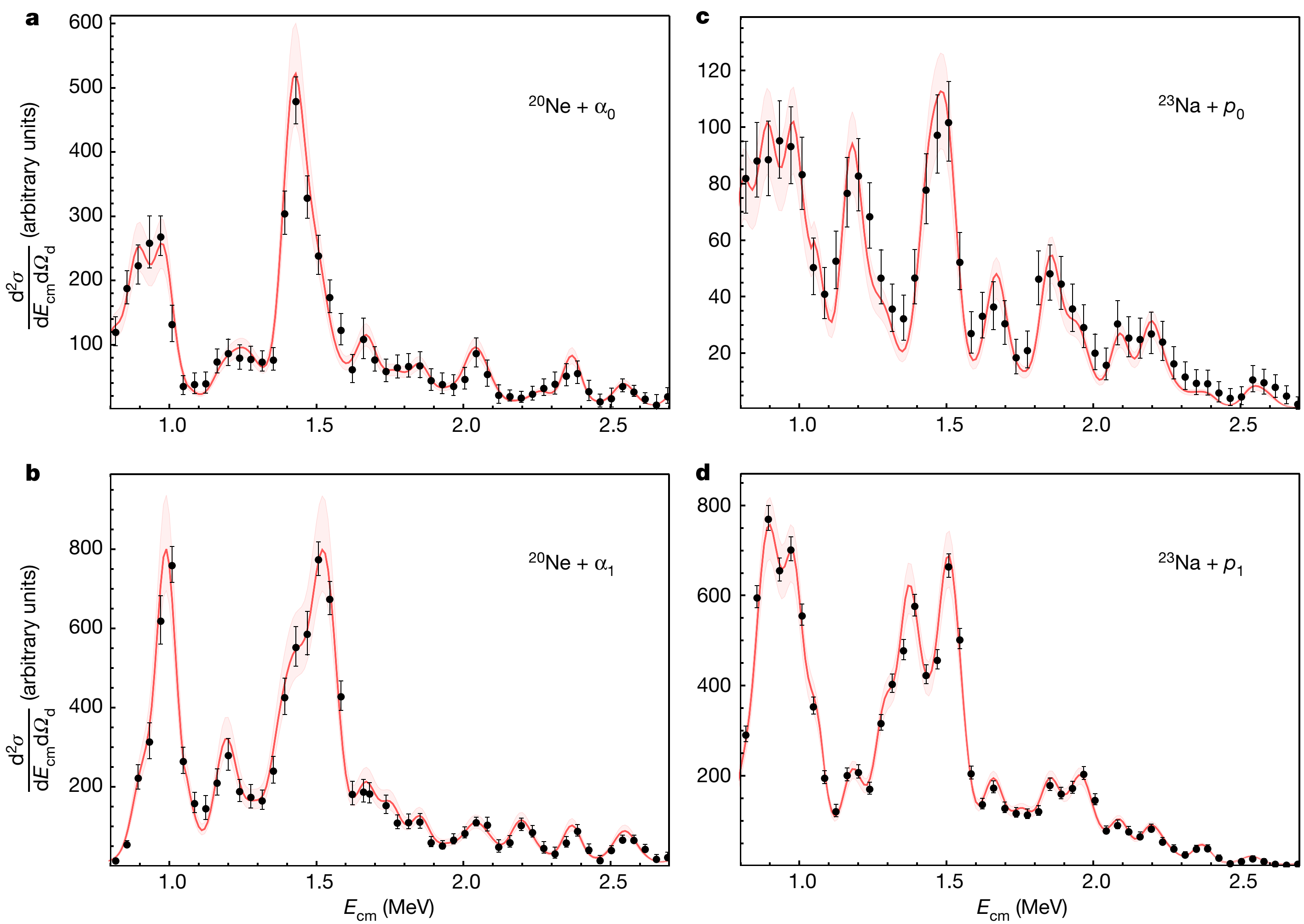
No definite conclusion!

→Thus, further measurements extending down to at least 1 MeV would be extremely important.

Our Experiment with theTHM

$^{12}C(^{12}C,\alpha)^{20}Ne$ and $^{12}C(^{12}C,p)^{23}Na$ reactions via the Trojan Horse Method 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 in quasi free kinematics

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



Red lines and bands: modified R-matrix fits for all channels at the same time

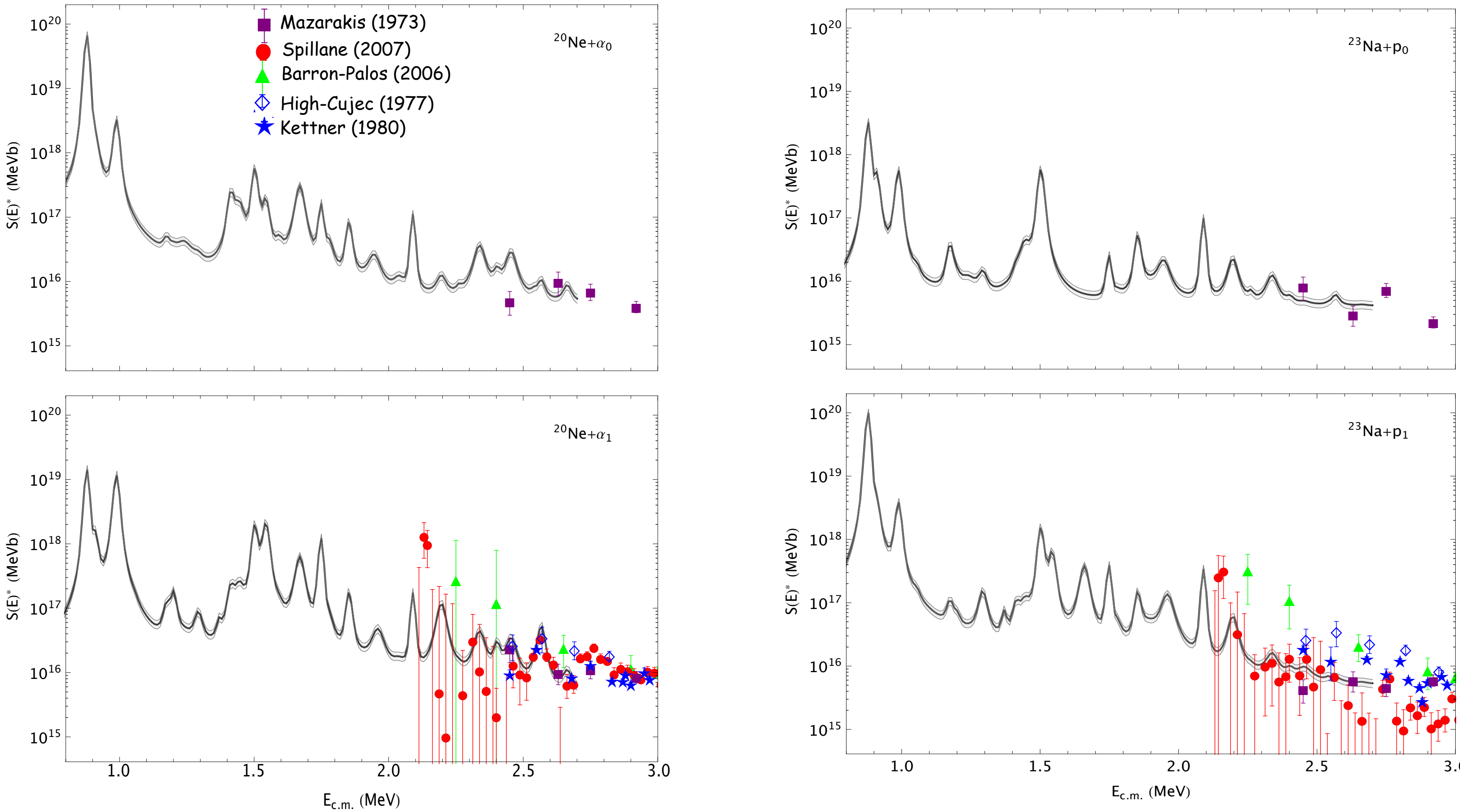
Reduced widths for known levels are used as free parameters to reproduce their total and partial widths as in Abegg & Davis, PRC 1991

S(E)* factors

$$S(E)^* = E\sigma(E)\exp(87.21E^{-1/2} + 0.46E) \quad (MeVb)$$

Normalization to direct data done in the E_{cm} window 2.50–2.63 MeV of the $^{20}Ne + \alpha_1$

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



Agreement between THM and direct data within the experimental errors except around 2.14 MeV, where THM data do not confirm the claim of a strong resonance;
nearby one at 2.095 MeV about one order of magnitude less intense in the $^{20}Ne + \alpha_1$ channel and with similar intensity in the $^{23}Na + p_1$ one

nature
International journal of science

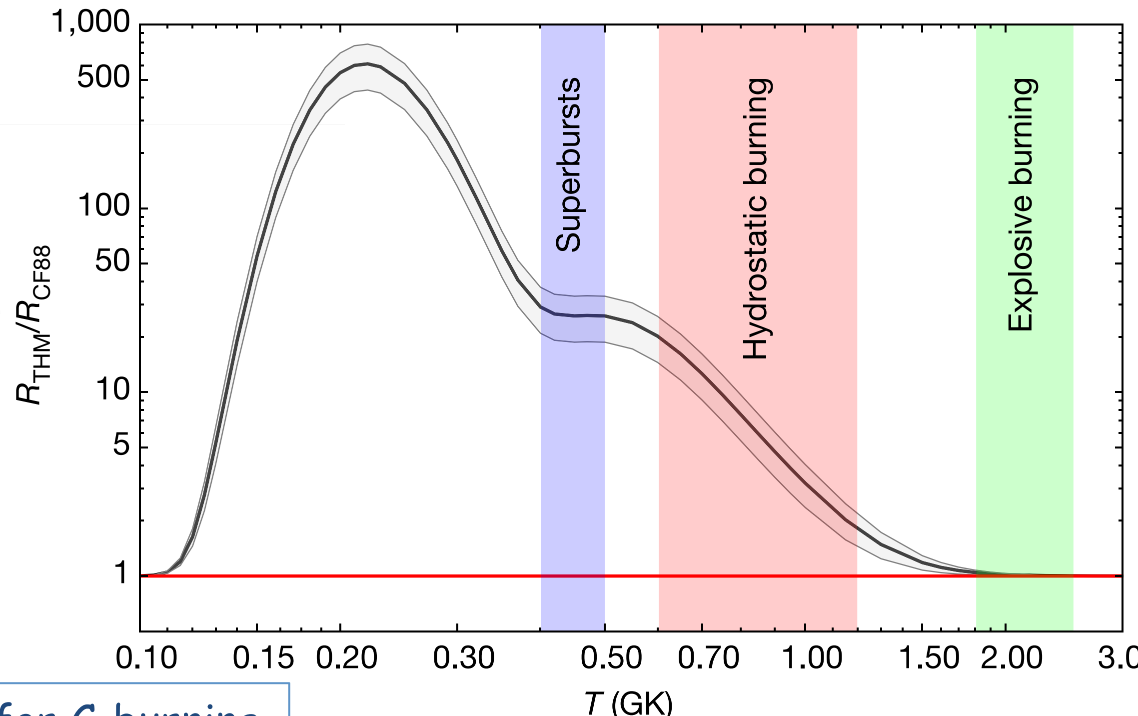
Letter | Published: 23 May 2018

An increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies

A. Tumino, C. Spitaleri, M. La Cognata, S. Cherubini, G. L. Guardo, M. Gulino, S. Hayakawa, I. Indelicato, L. Lamia, H. Petrascu, R. G. Pizzone, S. M. R. Puglia, G. G. Rapisarda, S. Romano, M. L. Sergi, R. Spartá & L. Trache

Nature **557**, 687–690 (2018) | Download Citation

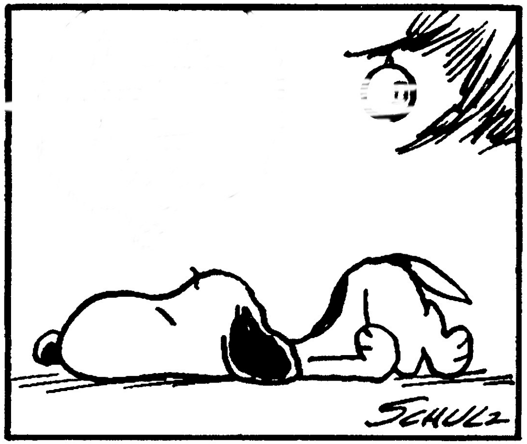
12C+12C Reaction Rate



Color shadings mark typical regions for C-burning

Compared to CF88, the present rate increases from a factor of 1.18 at 1.2 GK to a factor of more than 25 at 0.5 GK

Conclusions



Short !!!

- Indirect methods

→To extract cross-sections of astrophysical relevance in an energy range that cannot be reached with direct reactions.
→To obtain complementary information that cannot be extracted with direct experiments
→To confirm in another independent way already existing results of important reactions

- similar characteristics and theoretical concepts

- importance of nuclear reaction theory

- still great potential for future applications (also beyond astrophysical applications)!

Thank you for your attention!