Recent results in nuclear astrophysics with indirect methods

17th Russbach School on Nuclear Astrophysics

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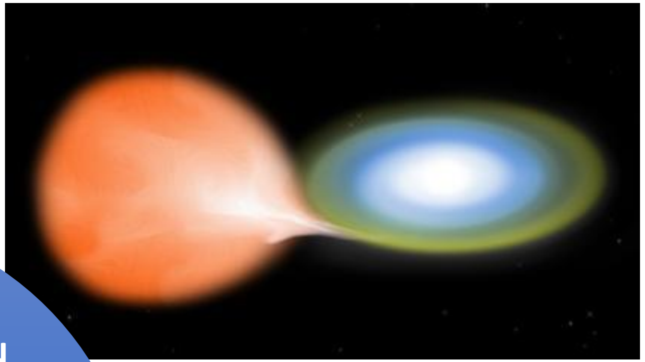
Nuclear astrophysics: from the laboratory to the cosmos

The purpose of nuclear astrophysics is to provide reliable nuclear physics input for astrophysical models



Nuclear parameters (cross sections, …)

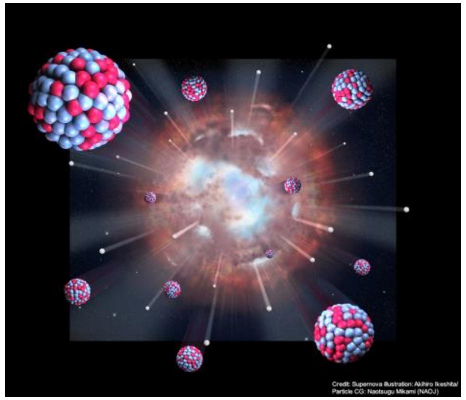
Astrophysical models: how a star works

Model input parameters: magnetic field, metallicity, …

Elemental yield → comparison with abundances observed in stars and meteorites to validate models

PROBLEM: cross sections are needed at energy of 10-100 keV

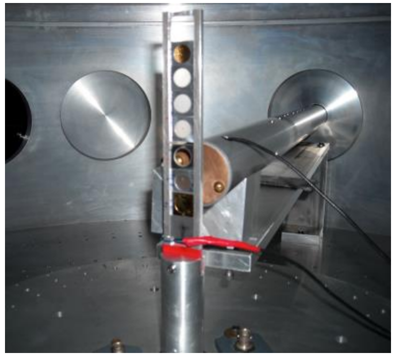
Change the model until observables are matched by predictions



Astrophysical models are very complex: assumptions on stellar structure and on stellar parameters (age, mass…) → need of multiple independent constraints

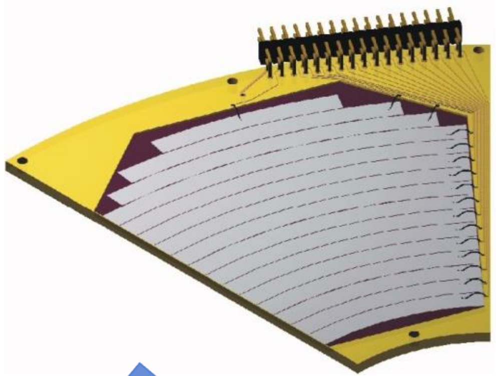
The need of indirect methods: direct vs. indirect methods

How to measure the A+x→c+C reaction in a *direct* way?

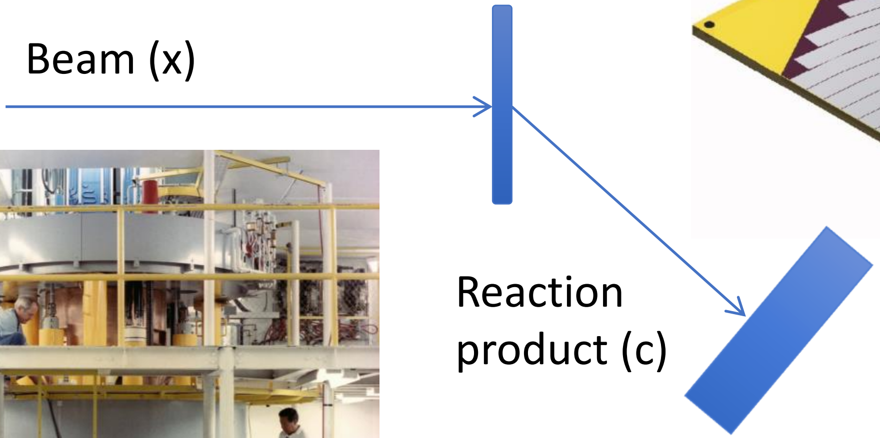


Target (A)

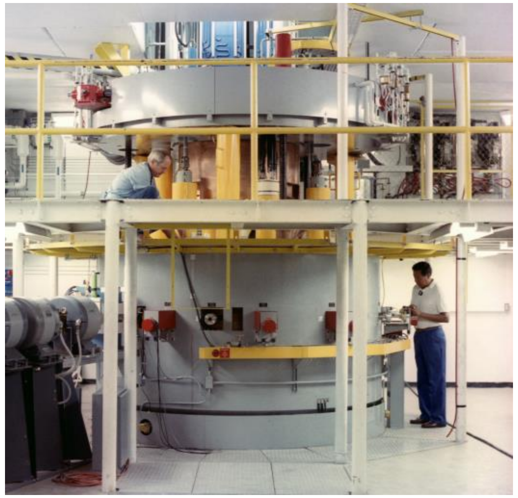
Detector → kinematic observables
- Energy
- Emission angle
& Particle identification



Beam (x)



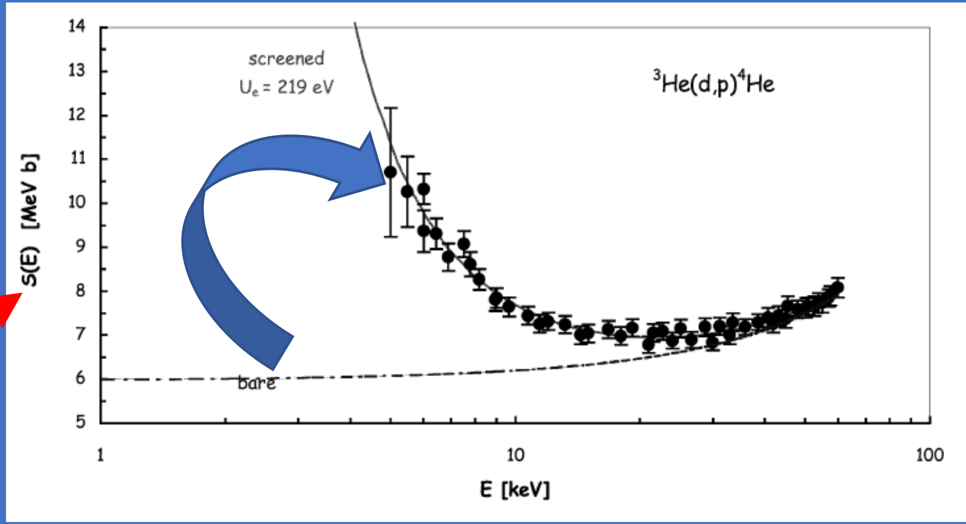
Reaction product (c)



It looks *quite* simple!

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

However, several reasons make the low-energy region of astrophysical interest difficult to access
- Coulomb barrier suppression of the cross section
- Cosmic background and systematic errors due to, e.g., straggling in the target
- ***Electron screening hiding the nuclear cross section***



The need of indirect methods: direct vs. indirect methods

Entrance channel:

A+a

Several reaction mechanisms link the two channels

Reaction products

C+c+…

Nuclear reaction theory required

→ cross checks of the methods needed

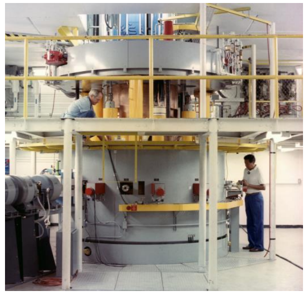
→ possible spurious contribution

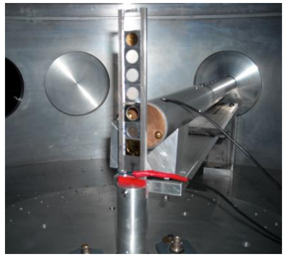
→ additional systematic errors (is the result model independent?)

Advantages include no need of low energies → no straggling, no Coulomb suppression, no electron screening

Possibility to access astrophysical energies with high accuracy

To recall the previous sketch:





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Nuclear reaction theory

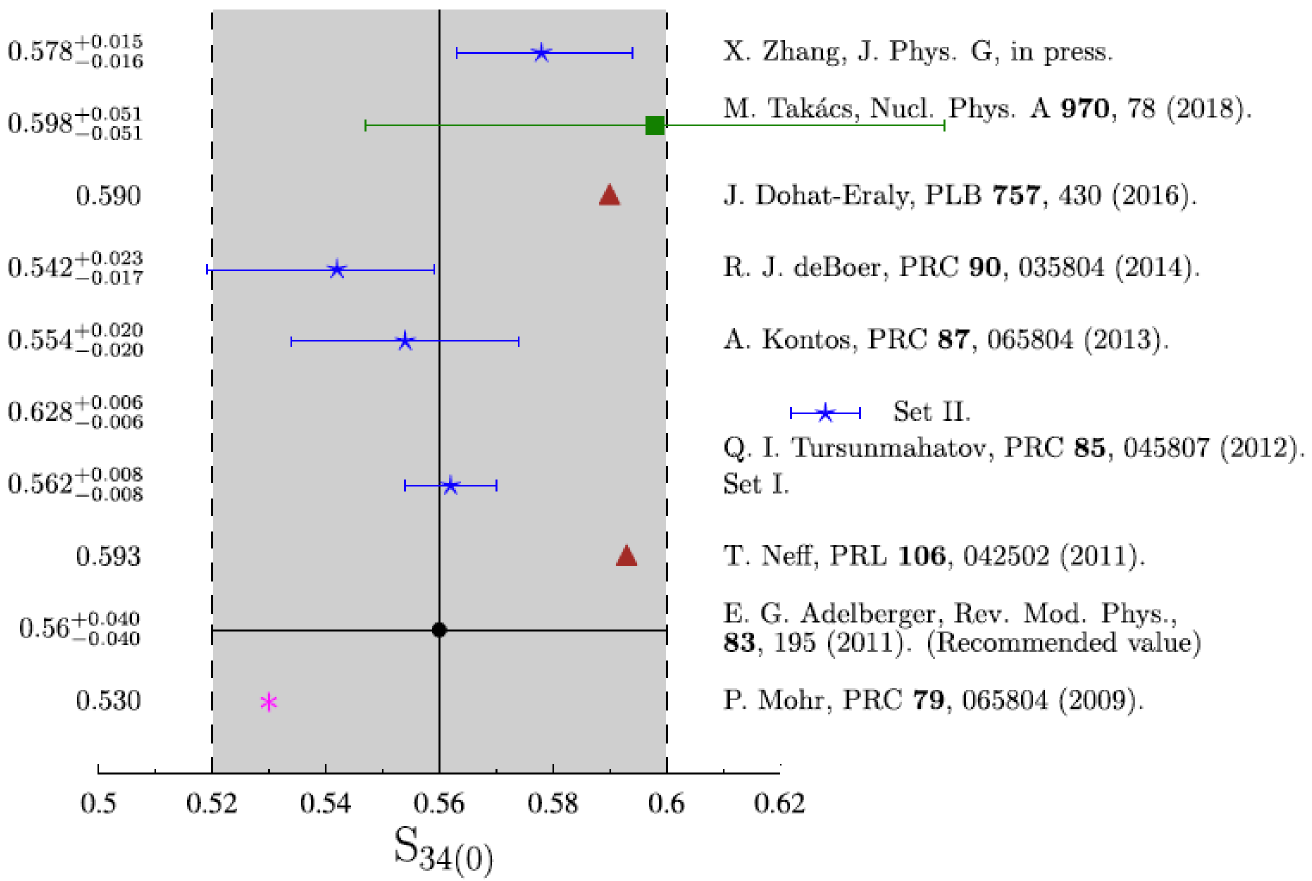
R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

Indirect methods are especially useful in the case of reactions involving **radioactive nuclei**

- Higher cross sections
- Possibility to study reactions induced by neutrons on radioactive nuclei
- Reactions among unstable nuclei
- Easier experimental procedures

PART 1: ANC

The $^3He(\alpha,\gamma)^7Be$ and the $^6Li(p,\gamma)^7Be$ scientific cases



The zero-energy astrophysical factor of the ^{3}**He(α,γ)**^{7}**Be** shows a very large scatter. There is no general agreement between measurement (prompt vs activation) and calculations → NEED OF NEW INDEPENDENT DATA

The detection of the neutrinos coming directly from the core of the Sun became more and more precise after the construction of larger and more efficient neutrino detectors

Neutrinos are released in the β decay of the ^7Be, ^8B, ^{13}N, ^{15}O isotopes produced in the p−p chain and in the CNO cycle.

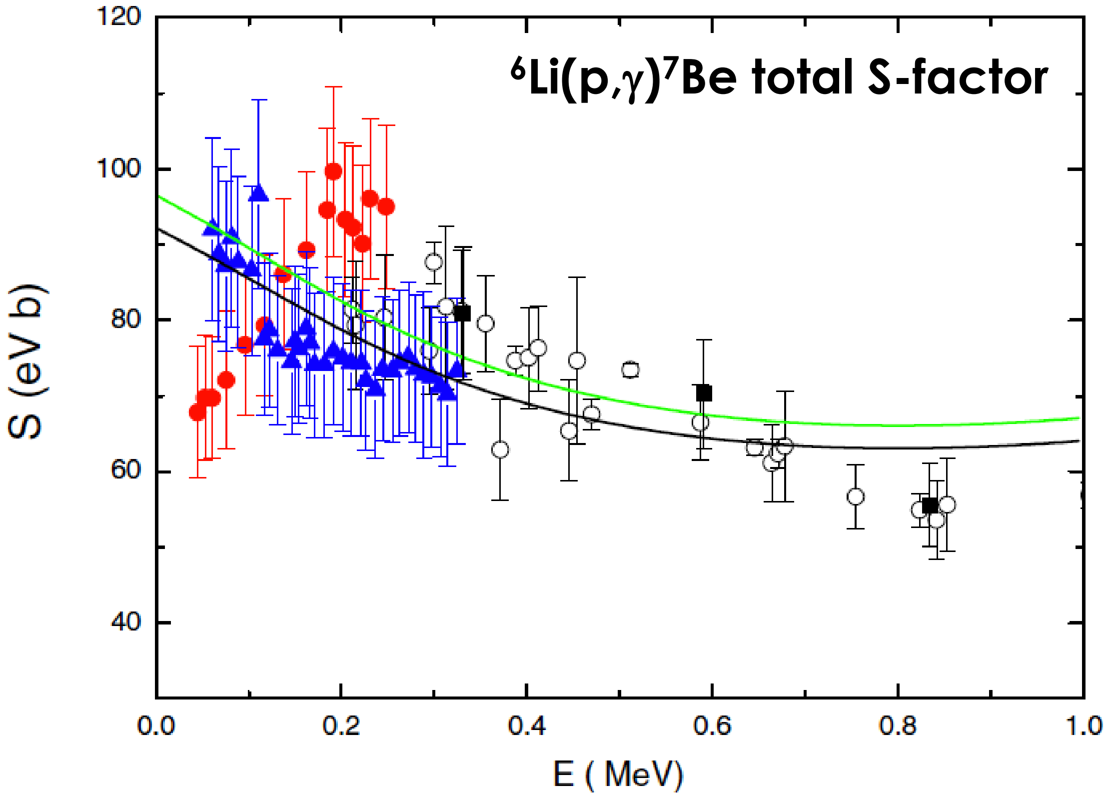
The flux of the p−p neutrinos was measured with a precision of about 3.4% by the BOREXINO, SNO and Super-Kamiokande collaborations

The precise neutrino flux measurements can constrain the Standard Solar Model (SSM)

However, at present the uncertainties on cross sections are far too high, typically of the order of 5-8% contrary to the 3% precision required

The ANC approach has the opportunity

The $^3He(\alpha,\gamma)^7Be$ and the $^6Li(p,\gamma)^7Be$ scientific cases



Blue solid triangles → D. Piatti et al., Phys. Rev. C 102, 052802(R) (2020) (including systematic error)

Red filled circles → J. J.He et al., Phys. Lett. B 725, 287 (2013)

Direct measurements show a totally different low energy trend

Lithium is a key elements in astrophysics as big bang nucleosynthesis models coupled to chemical evolution models fail to find an agreement between predictions and observations.

^{7}Li is the most abundant isotope, produced in the BBN and in stars

^{6}Li is almost exclusively produced by cosmic rays and the possibility of a primordial ^{6}Li plateau, like the one for ^{7}Li, is not presently confirmed

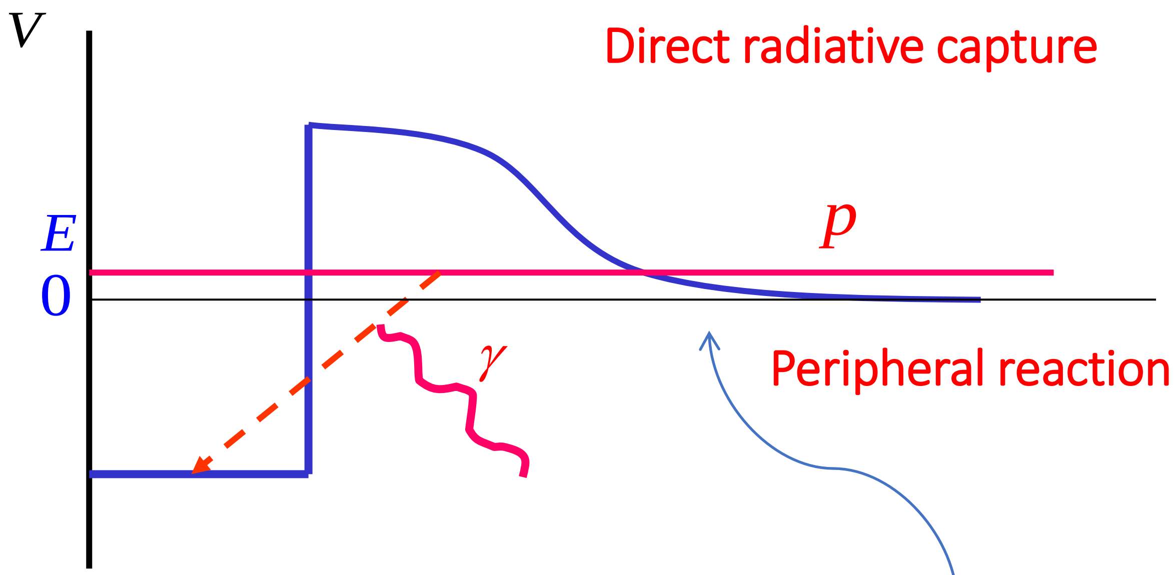
Since the production mechanism of ^{6}Li and ^{7}Li are completely different, the ^{6}Li/^{7}Li isotopic ratio can be used either to constrain the lithium production mechanisms and/or the galactic enrichment processes

→ an accurate determination of the $^6Li(p,\gamma)\,^7Be$ astrophysical S factor is needed.

About the ANC (Asymptotic Normalization Coefficient) method

Radiative *p* (α) capture at stellar energies

- Classical **barrier penetration** problem



- **low energies $\Rightarrow$ capture at large radii**
- **very small cross sections**

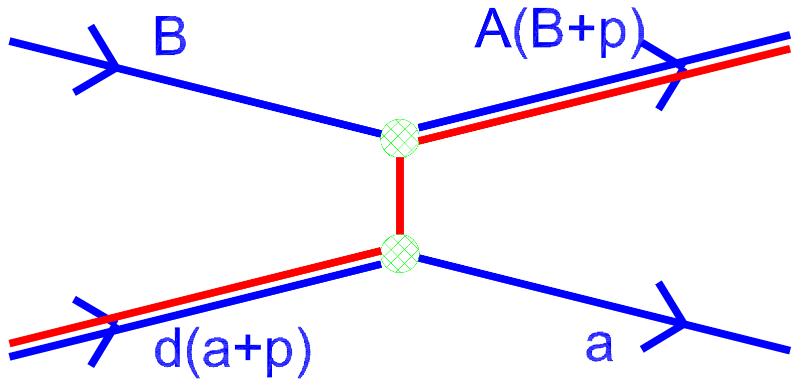
The cross section is determined by ANCs

$$\sigma \propto \left| M \right|^2 \qquad M = \left\langle I^{A}_{Bp}(r_{Bp}) \middle| \hat{O}(r_{Bp}) \middle| \psi_i^{(+)}(r_{Bp}) \right\rangle$$

Low B.E.: $$I^{A}_{Bp}(r_{Bp}) \overset{r_B > R_N}{\approx} C^{A}_{Bp} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

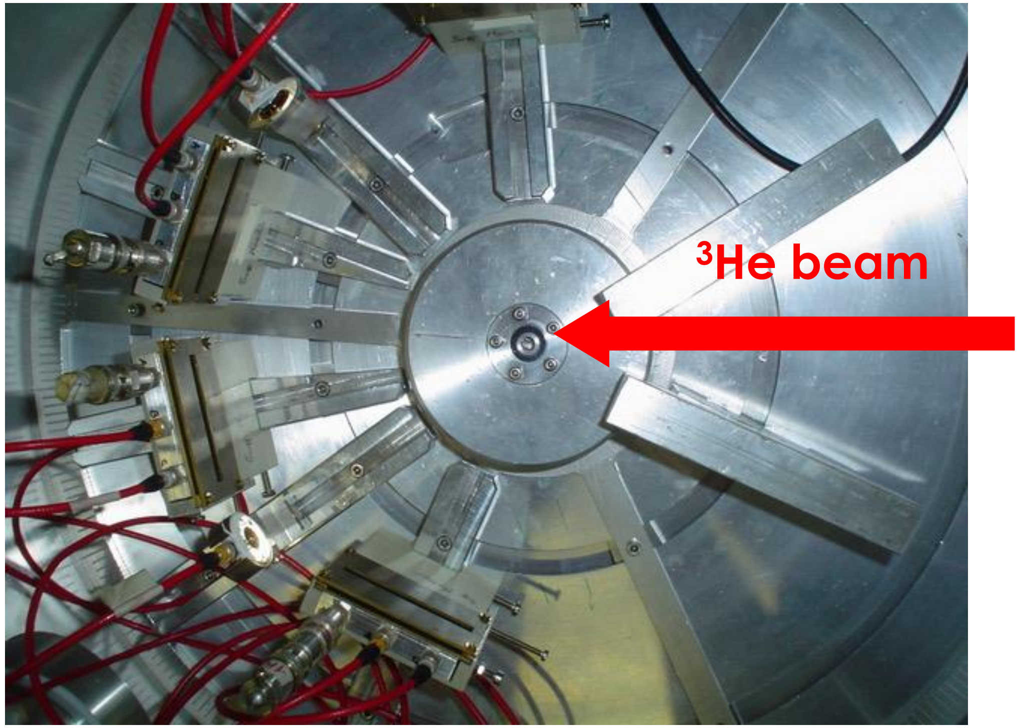
Outside the nuclear radius

Find: $$\sigma_{capture} \propto (C^{A}_{Bp})^2$$



ANC $\Rightarrow$ amplitude for tail of overlap function → can be deduced from transfer reaction XS

The $^{6}Li(^{3}He,d)^{7}Be$ measurement

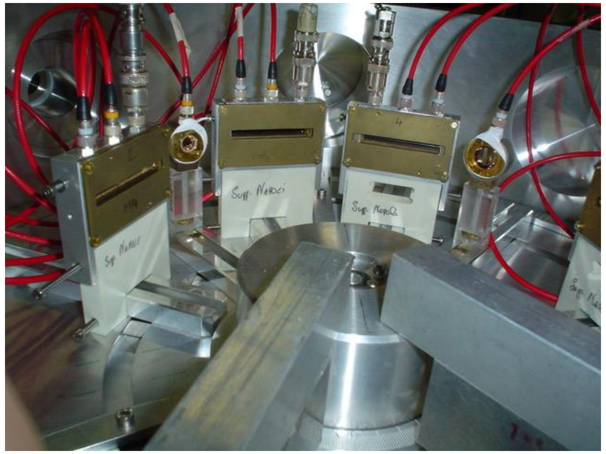


Experimental setup

^{3}He beams by: **singletron accelerator @ Department of Physics and Astronomy** (DFA) of the University of Catania (Italy) **and FN tandem accelerator @ John D. Fox Superconducting Accelerator** Laboratory at Florida State University (FSU), Tallahassee (FL), USA

Angular distributions were measured at **E_{lab} = 3 MeV and E_{lab} =5 MeV** using silicon DE-E telescopes on a turntable. Additional monitor detectors were placed at symmetric angles with respect to the beam axis to check target thickness and for normalization.

^{6}LiF (enriched in ^{6}Li by 95%) and pure ^{6}Li targets (enriched in ^{6}Li by 98%) were used



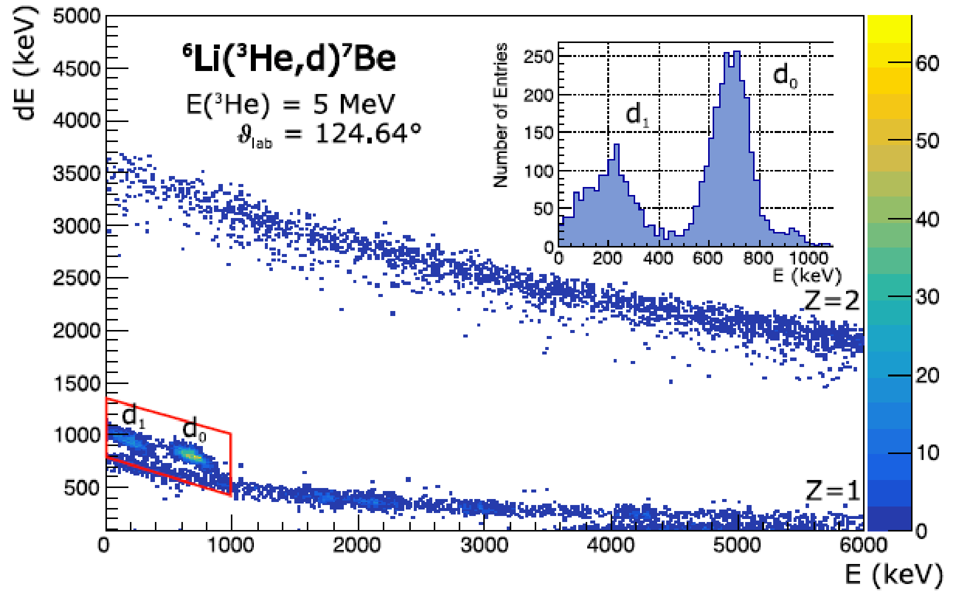
The experimental team

AsFiN

The ASFIN collaboration

Experimental spectra

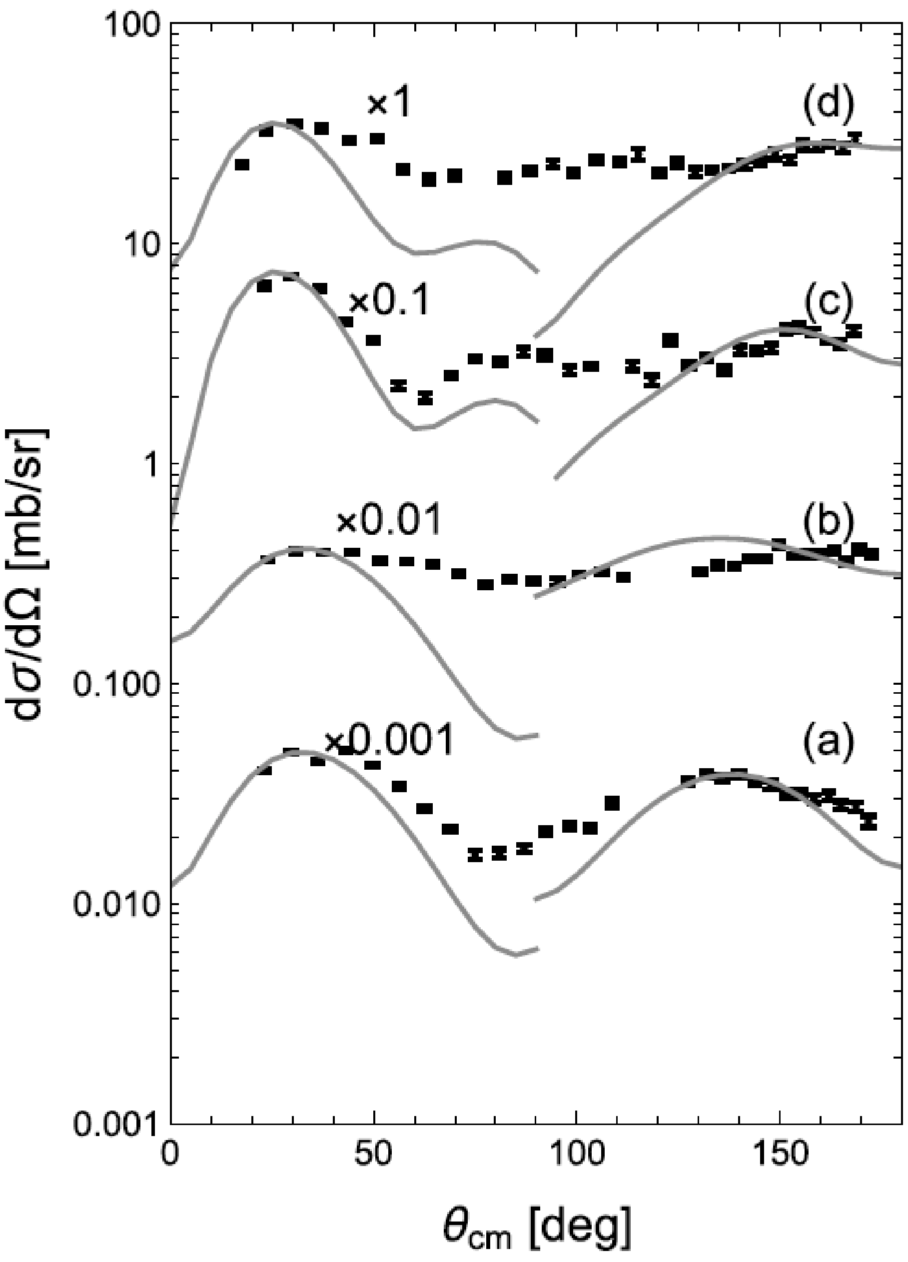
G.G. Kiss et al. Physics Letters B 807 (2020) 135606
G.G. Kiss et al. Physical Review C 104 (2021) 015807



DE−E spectrum measured with a silicon telescope

The peaks: d_0 and d_1

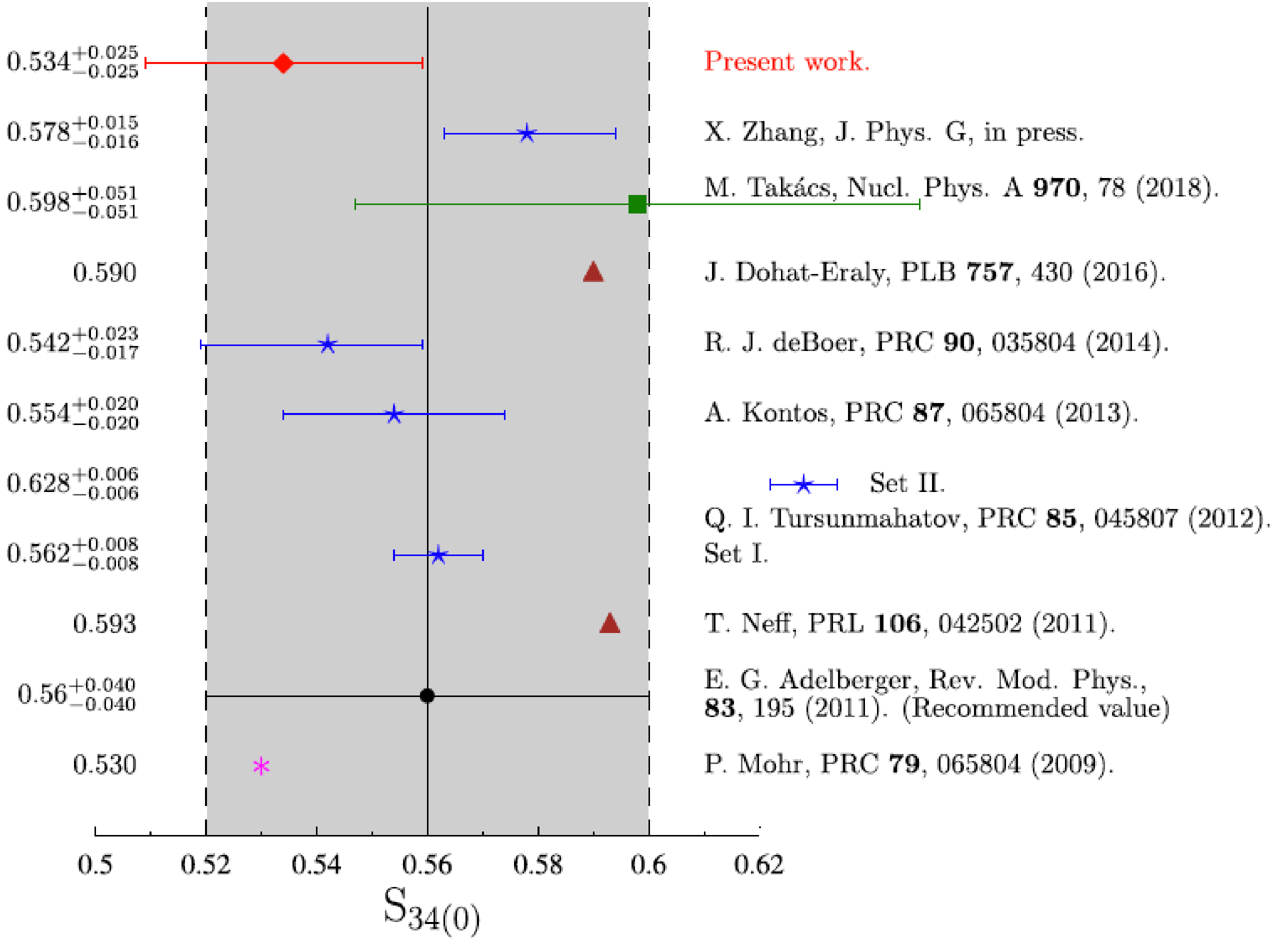
1. Very clean d ID
2. Observation of both ^{7}Be gs and 1st excited state



Angular distributions of the ^{6}Li(^{3}He,d)^{7}Be reaction populating the ground ((a) and (c)) and first (0.429 MeV) excited ((b) and (d)) states of ^{7}Be at the projectile ^{3}He energies of 3 ((a) and (b)) and 5 ((c) and (d)) MeV.

Gray lines are the calculated angular distributions, **for p−and α−transfer (forward and backward hemisphere, respectively) → possibility to deduce the ANC's for both channels** (no interference at the peaks)

The ^{3}He(α,γ)^{7}Be $S_{34}(0)$ using ANC



- **Lower $S_{34}(0)$ values favored, with a total uncertainty equal to 4.7%.**
- **More than 50% of the error budget is due to the non-peripherality of the transfer process**

The post-form DWBA calculation contains:

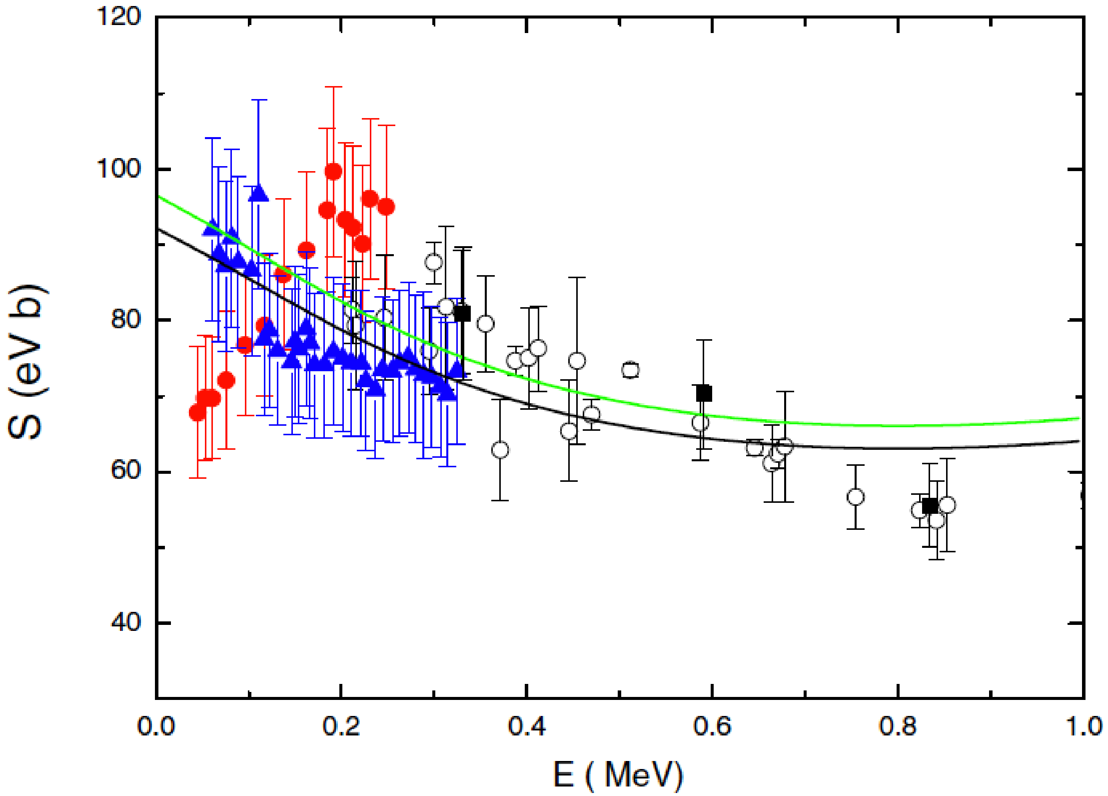
- ✓ s-wave ANC values for the d+p →^{3}He and the d+α→^{6}Li channels
- ✓ Test of the dependence on the choice of the optical potentials
- ✓ Test of the peripheral nature of the reaction
- ✓ channels coupling effects (CCE)

Further improvements to be implemented:

- ○ Test one-step process in modelling the transfer
- ○ Test the coupling between ground and excited states of ^{6}Li and ^{7}Be
- ○ Perform full coupled-channel analysis to derive the ^{3}He+^{4}He and the *p*+^{6}Li ANCs

^{3}He(α,γ)^{7}Be
PLB 807 (2020) 135606

The ^{6}Li(p,γ)^{7}Be astrophysical factor



Green line: astrophysical S factor obtained by using the weighted average ANC values from the near-barrier proton transfer ^{6}Li(^{3}He,d)^{7}Be reaction at E_{beam} = 3 and 5 MeV
Black line: astrophysical S factor obtained from the analysis of the ^{6}Li(p,γ)^{7}Be S-factor of Piatti et al. (2020)

Our result strongly disfavors the resonant trend claimed by He et al. (2014)

Two approaches:

1. the weighted means of the ANCs from the analysis of the ^{6}Li(^{3}He,d)7Be transfer were used to calculate the total astrophysical S factor for the ^{6}Li(p,γ)^{7}Be reaction **using the modified two-body potential method [Igamov and R. Yarmukhamedov (2019)]**. In the calculation M1 and E2 are neglected as their contribution is lower than 1% at these energies

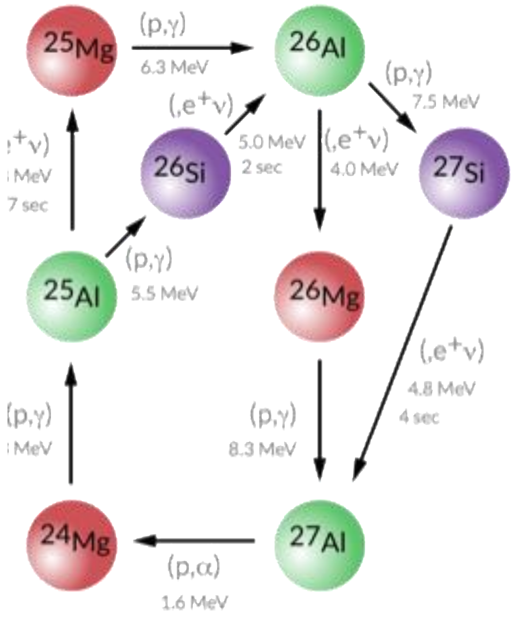
2. the ANCs for the ^{6}Li+p→ ^{7}Be(g.s.) and ^{6}Li+p→ 7Be(0.429 MeV) channels were derived from the experimental total astrophysical S factor and the branching ratios of Piatti et al. (2020) and then (**after checking the actual agreement**), we also calculated the astrophysical factor of the ^{6}Li(p,γ)7Be reaction within the MTBPM

^{6}Li(p,γ)^{7}Be
PRC 104 (2021) 015807

PART 2: THM

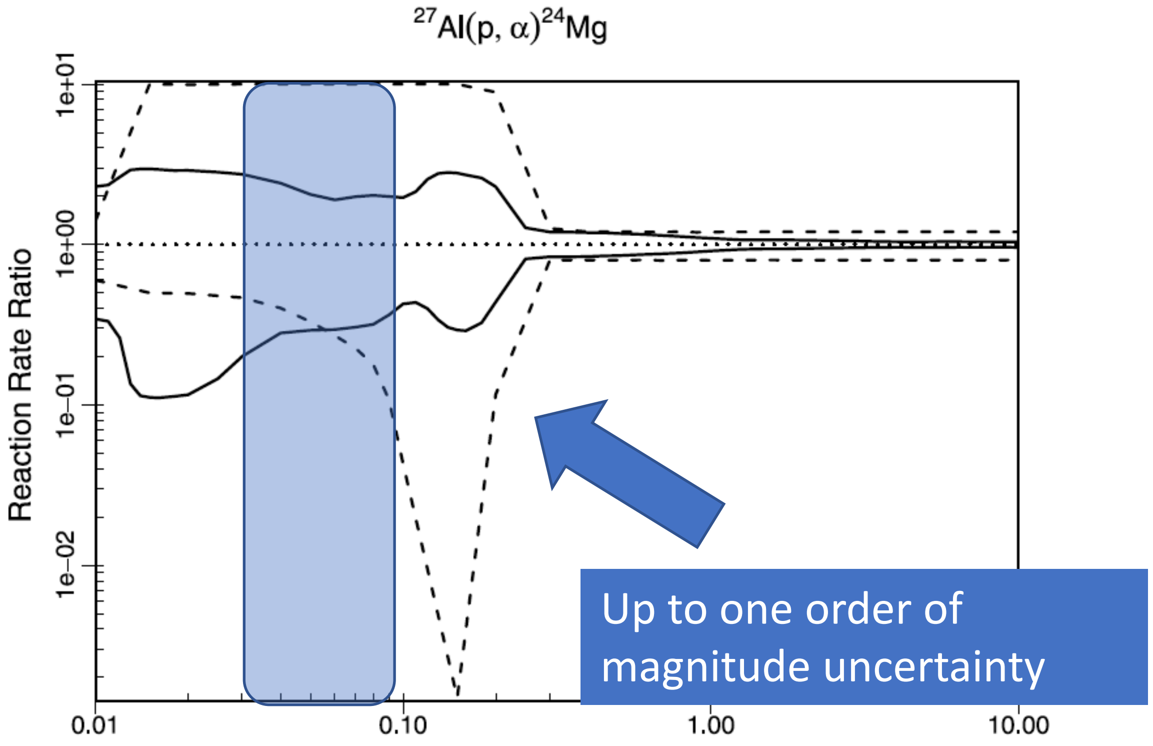
The $^{27}Al(p,\alpha)^{24}Mg$ reaction

MgAl cycle in massive stars

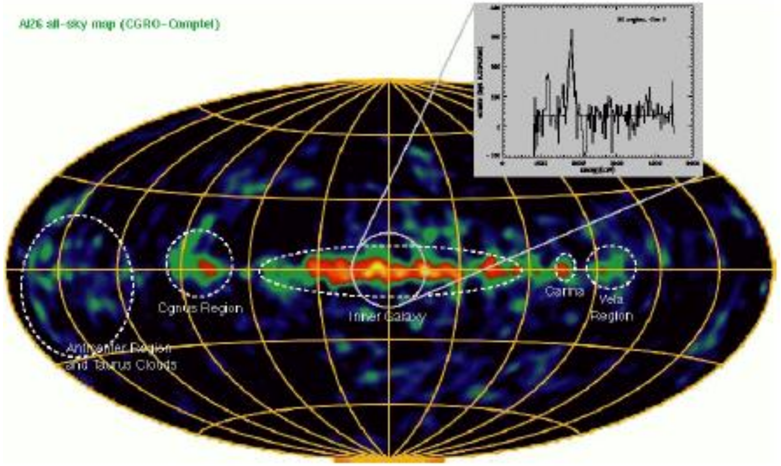


Mg-Al Cycles

It is ignited at temperatures > 0.03 GK and it is important to determine the abundances of medium mass nuclei

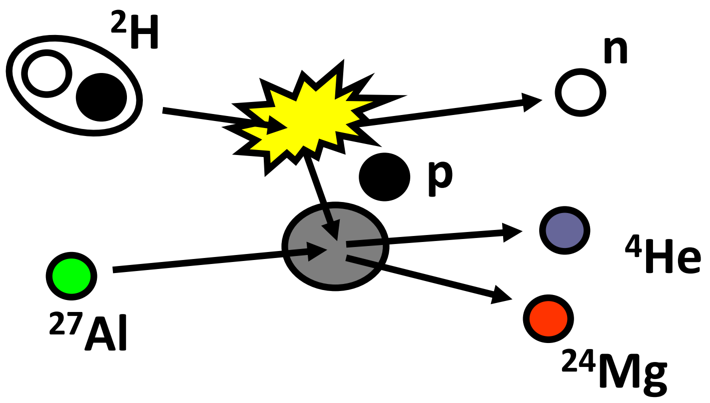


$^{26}Al/^{27}Al$ abundance ratio



^{26}Al abundance is used to estimate the number of Galactic neutron stars and, therefore, of neutron star mergers (sources of GW). The $^{26}Al/^{27}Al$ is generally estimated, so it is influenced by ^{27}Al abundance predictions

The Trojan Horse Method (THM)



When narrow resonances dominate the S-factor the reaction rate can be calculated by means of the resonance **strengths and resonance energies only**. Both can be deduced from the THM cross section.

Let's focus on resonance strengths

$$\omega\gamma_i = \frac{2J_i + 1}{(2J_p + 1)(2J_{^{27}\mathrm{Al}})} \frac{\Gamma_p^i \Gamma_\alpha^i}{\Gamma_{\mathrm{tot}}}$$

The strengths are calculated from resonance partial widths

What is its physical meaning?
Area of the Breit-Wigner describing the resonance

$$\omega\gamma_i^{\mathrm{THM}} \approx \omega_i N_i \frac{\Gamma^i_{p,\,\mathrm{s.p.}}}{\sigma_{(d,n)}(\theta_n^{c.m.})}$$

In the THM approach we determine the strength in arb.units. Normalization to a known resonance is necessary

Advantage:
no need to know the resonance shape (moderate resolution necessary)

THM: in the case of resonant reactions a metastable state is formed (^{28}Si), escaping the nuclear interaction region and later decaying to α+^{24}Mg

THM => Transfer to the continuum

ANC => Transfer to a bound state

In both cases peripherality has to be enforced

THM: Basic features

Plane Wave Impulse Approximation:

- **beam energy >> a = x ⊕ b breakup Q-value**
- **projectile wavelength k^{-1} << x – b intercluster distance**

  + plane waves in the entrance and exit channel

➔ the 3-body cross section factorizes:

$$\frac{d^3\sigma}{dE_C\, d\Omega_C\, d\Omega_c} \propto \mathrm{KF}\,|\phi(-\vec{p}_b)|^2 \cdot \left(\frac{d\sigma}{d\Omega_{c.m.}}\right)^{\mathrm{off}}$$

From the experiment

Evaluated through a MC code

HOES 2-body cross section

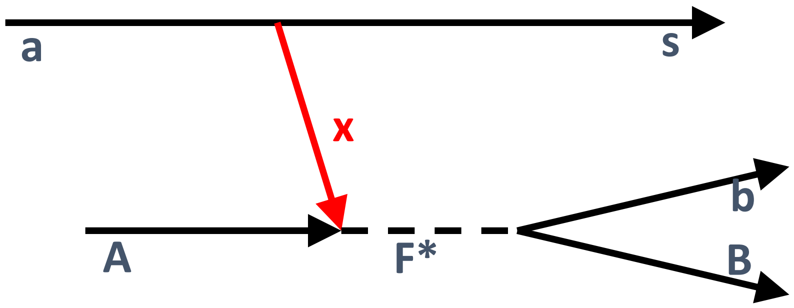
- **KF kinematic factor**
- **$\phi(p_b)^2$ spectator momentum distribution**
- **$d\sigma^{off}/d\Omega$ off-shell cross section or "nuclear" (N) cross section**

$d\sigma^{off}/d\Omega$ ➔ $d\sigma/d\Omega$ (on shell)

The penetration factor P_l has to be introduced:

$$\frac{d\sigma}{d\Omega} = \sum_l P_l \frac{d\sigma_l^N}{d\Omega}$$

The full THM: the resonant case (A. Mukhamedzhanov)



R. Tribble et al., Rep. Prog. Phys. **77** (2014) 106901

In the latest years, large efforts were made to give a quantitative justification of THM, to estimate the uncertainties and improve the description of the 2→3 cross section

Amplitude of

Same R-matrix term as in OES cross section but for the appearence of the inverse penetration factor making it possible to observe suppressed resonances at low energies negligigle at usual experimental precisions

$$
\begin{aligned}
M^{\mathrm{PWA(prior)}}(P, \boldsymbol{k}_{aA}) = {} & (2\pi)^2 \sqrt{\frac{1}{\mu_{bB} k_{bB}}}\, \varphi_a(\boldsymbol{p}_{sx}) \\
& \times \sum_{J_F M_F j' l l' m_{j'} m_l m_{l'} M_n} i^{l+l'} \langle j m_j l m_l | J_F M_F \rangle \langle j' m_{j'} l' m_{l'} | J_F M_F \rangle \\
& \times \langle J_x M_x J_A M_A | j' m_{j'} \rangle \langle J_s M_s J_x M_x | J_a M_a \rangle\, \mathrm{e}^{-\mathrm{i}\delta^{hs}_{bBl}}\, Y_{l m_l}(-\hat{\boldsymbol{k}}_{bB}) \\
& \times \sum_{\nu,\tau=1}^{N} [\Gamma_{\nu bBjlJ_F}(E_{bB})]^{1/2} [\boldsymbol{A}^{-1}]_{\nu\tau}\, Y^*_{l' m_{l'}}(\hat{\boldsymbol{p}}_{xA}) \\
& \times \sqrt{\frac{R_{xA}}{\mu_{xA}}} [\Gamma_{\tau xAl'j'J_F}(E_{xA})]^{1/2} P_{l'}^{-1/2}(k_{xA}, R_{xA}) \big(j_{l'}(p_{xA} R_{xA}) \\
& \times [(B_{xAl'}(k_{xA}, R_{xA}) - 1) - D_{xAl'}(p_{xA}, R_{xA})] \\
& + 2 Z_x Z_A e^2 \mu_{xA} \int_{R_{xA}}^{\infty} \mathrm{d}r_{xA} \frac{O_{l'}(k_{xA}, r_{xA})}{O_{l'}(k_{xA}, R_{xA})} j_{l'}(p_{xA} r_{xA}) \big).
\end{aligned}
$$

Fourier transform of the s-x relative motion wave function

solid sphere scattering phase shift

Inverse penetration

R-matrix-like boundary condition

THM vs. OES astrophysical factor

Direct data:

$$S(E_{xA}) = \frac{\mu_{cC}\,\mu_{xA}}{4\pi^2}\frac{k_{cC}}{k_{xA}}\frac{1}{\hat{J}_x\hat{J}_A}E_{xA}\,e^{2\pi\eta_{xA}} \times \left|\sum_{\nu,\tau=1}^{2}\tilde{V}_{\nu cC}(E_{cC})\,[\mathbf{D}^{-1}]_{\nu\tau}\,\tilde{V}_{\tau xA}(E_{xA})\right|^2$$

Remember that:

$$\tilde{\Gamma}_{\nu c}(E_c) = 2\pi|\tilde{V}_{\nu c}(E_c)|^2$$

is the formal partial resonance width for the decay of this level into channel c=x+A or c=b+B.

THM data:

$$S^{\mathrm{TH}}(E_{xA}) = \frac{\mu_{cC}\,\mu_{sF}\,\mu_{aA}}{2\pi^5}\frac{k_{cC}\,k_{sF}}{k_{aA}}\frac{1}{\hat{J}_a\hat{J}_A}E_{xA}\,e^{2\pi\eta_{xA}} \times \Gamma_{2xA}(E_{xA})\left|\sum_{\nu,\tau=1}^{2}\tilde{V}_{\nu cC}(E_{cC})\,[\mathbf{D}^{-1}]_{\nu\tau}\,L_{2\tau}(\mathbf{k}_{sF},\mathbf{k}_{aA})\right|^2$$

Where:

$$L_{2\tau}(\mathbf{k}_{sF},\mathbf{k}_{aA}) = \frac{M_\tau(\mathbf{k}_{sF},\mathbf{k}_{aA})}{M_2(\mathbf{k}_{sF},\mathbf{k}_{aA})}$$

It can be calculated (DWBA, CDCC, PWBA…) or taken from measurements

The matrix $\mathbf{D}^{-1}$ and $V_{\nu cC}(E_{cC})$ are the same in the TH and OES astrophysical factors.
The THM S-factor does not contain the penetration factor, which has to be inserted for comparison with direct data

Moreover: exploring negative energies with the THM

Using the kinematics of three body reactions:

$$E_{Ax} = \frac{m_x}{m_x + m_A} E_A - \frac{p_s^2}{2\mu_{sF}} + \frac{\mathbf{p}_s \cdot \mathbf{p}_A}{m_x + m_A} - \varepsilon_{sx}$$

s-x Fermi motion

s-x binding energy

It is possible to achieve negative energies in the A-x channel

How to deal with negative energies? what is their meaning?

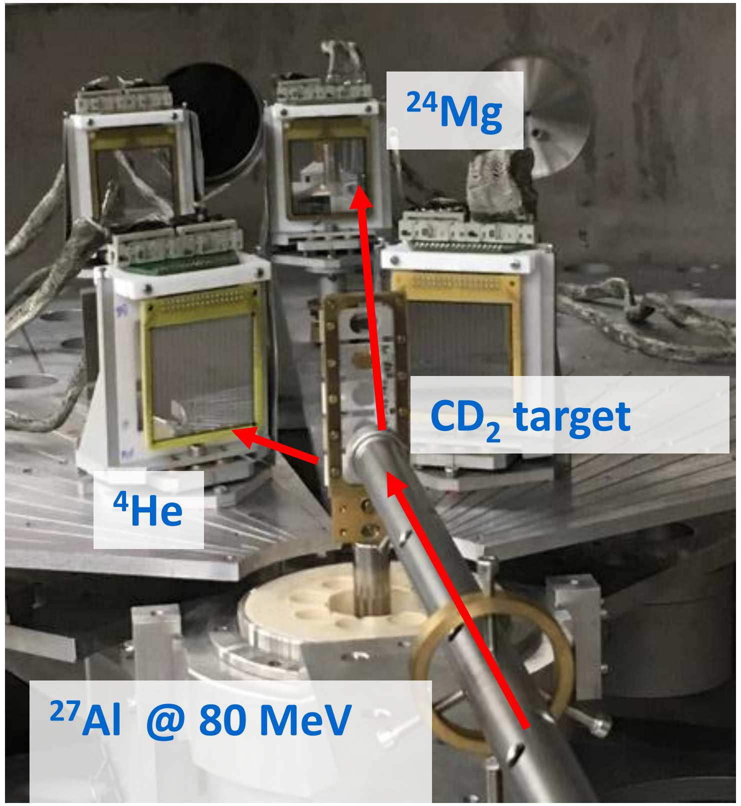
Standard R-Matrix approach cannot be applied to extract the resonance parameters of the A(x,c)C reaction because x is virtual —> Modified R-Matrix is introduced instead (A. Mukhamedzhanov 2010)

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

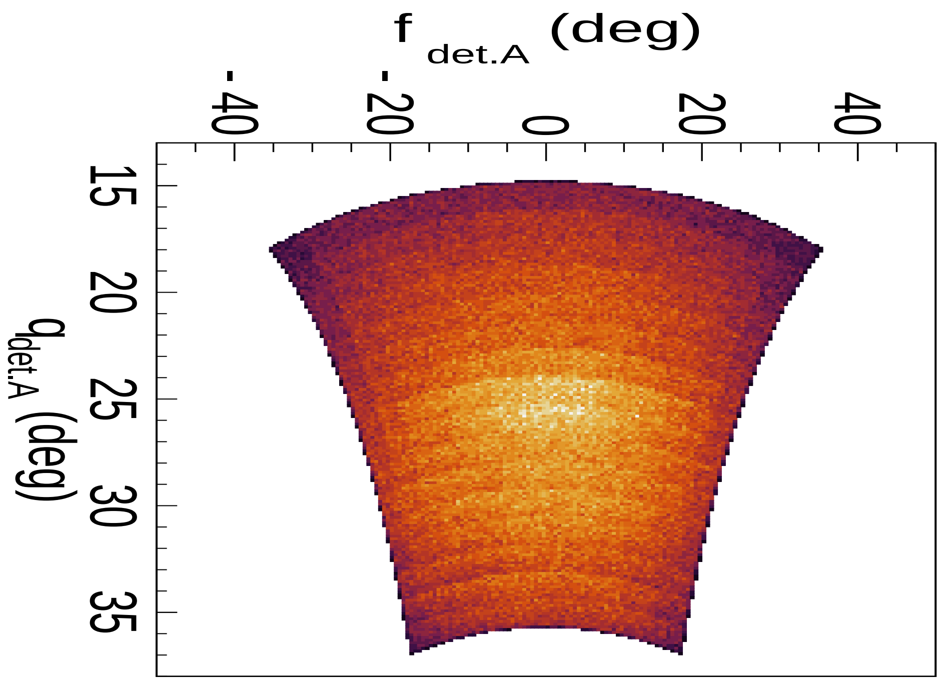
At negative energies M^2 is given by the product of the Whittaker function and the ANC of the F state populated in the transfer reaction

Merging together ANC and THM —> deep connection of these two indirect methods

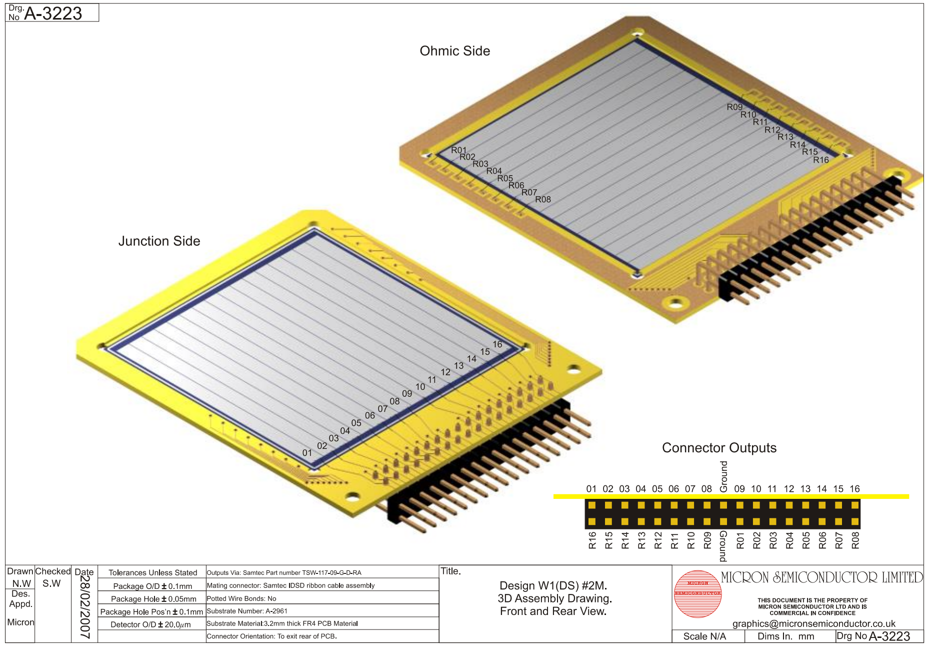
The $^{2}H(^{27}Alp,\alpha^{24}Mg)n$ reaction study



From LNS Tandem



The experiment was carried out by local people only, though the proposal included 25 people from 7 countries → **international effort**

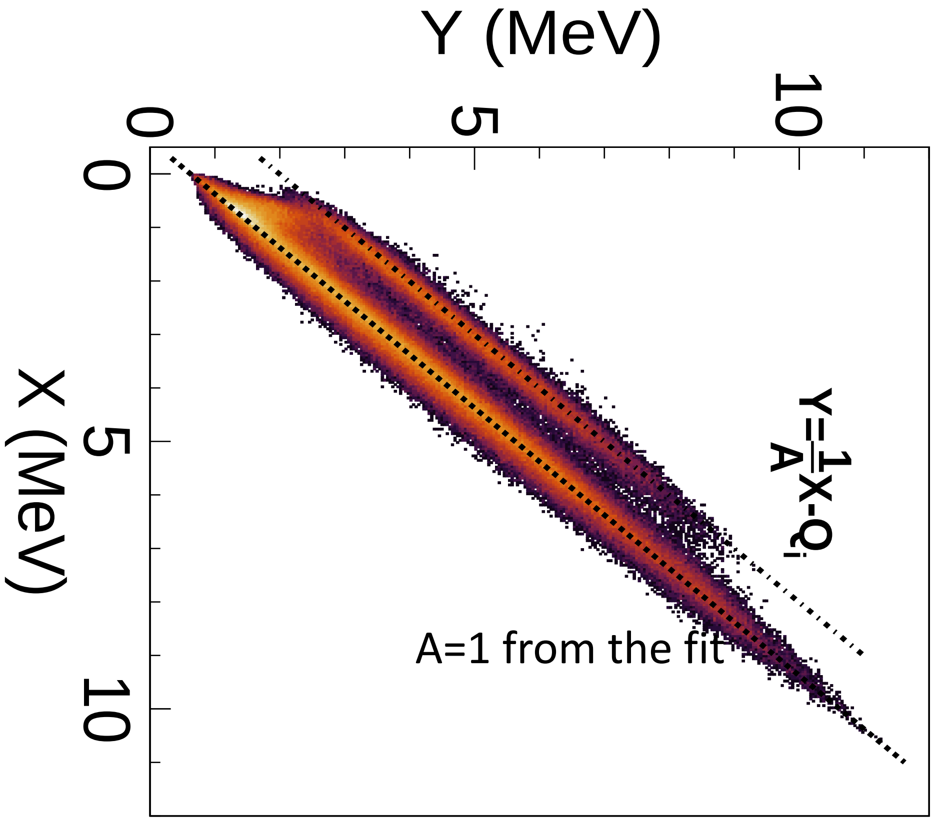


INFN
LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

The experiment at INFN-LNS Catania (right after the end of national lockdown in spring 2020)

PI: F. Hammache (Orsay) – S. Palmerini (PG)

Reaction channel selection

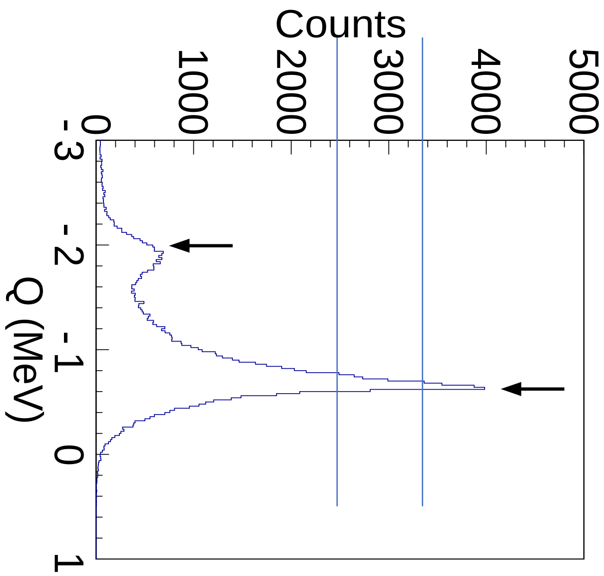


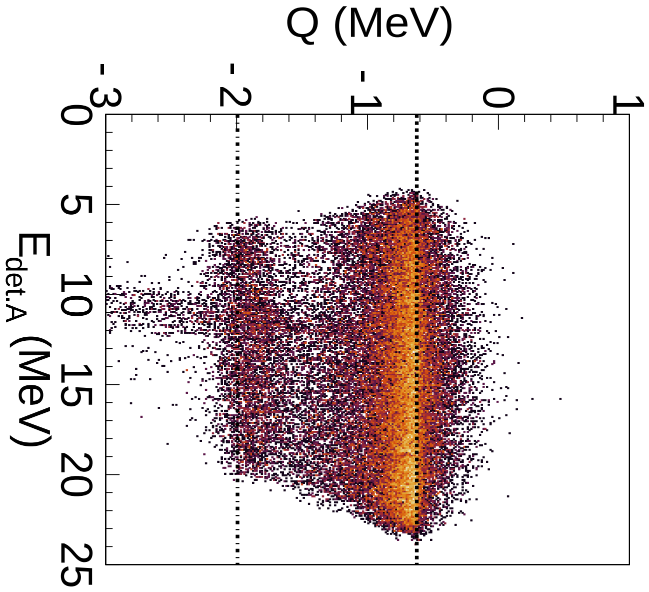
First the mass of the undetected particle is **deduced** from the energy conservation law:

$Y=E_{beam}-E_A-E_C$

$X=p_A^2/2u$

Then the Qvalue spectrum is reconstructed



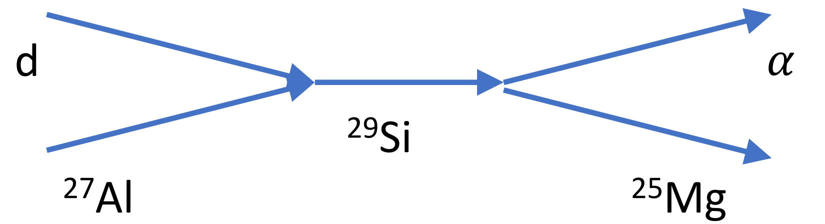


Two peaks for ^{24}Mg gs and 1st excited

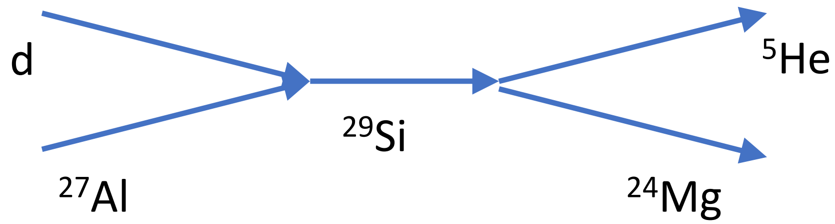
Arrows: theoretical Qvalues

No additional peaks are found, meaning that no spurious processes are seen
However, some background is present, but to the percent level for ^{24}Mg ground state contribution

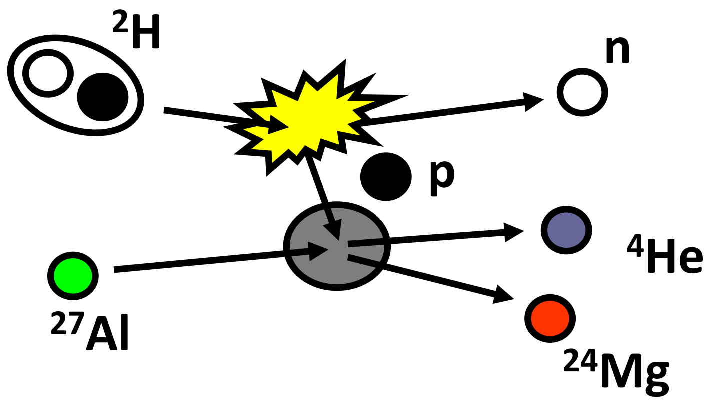
Evidence of the quasi-free reaction mechanism

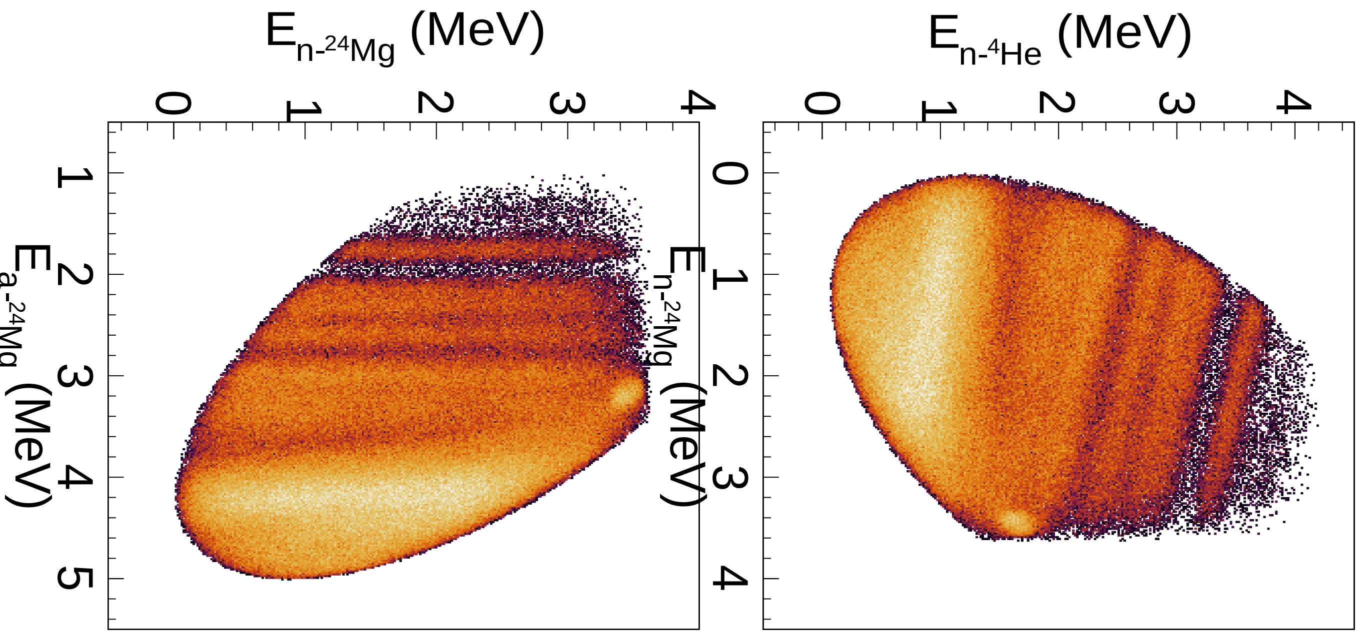


Possible non QF processes

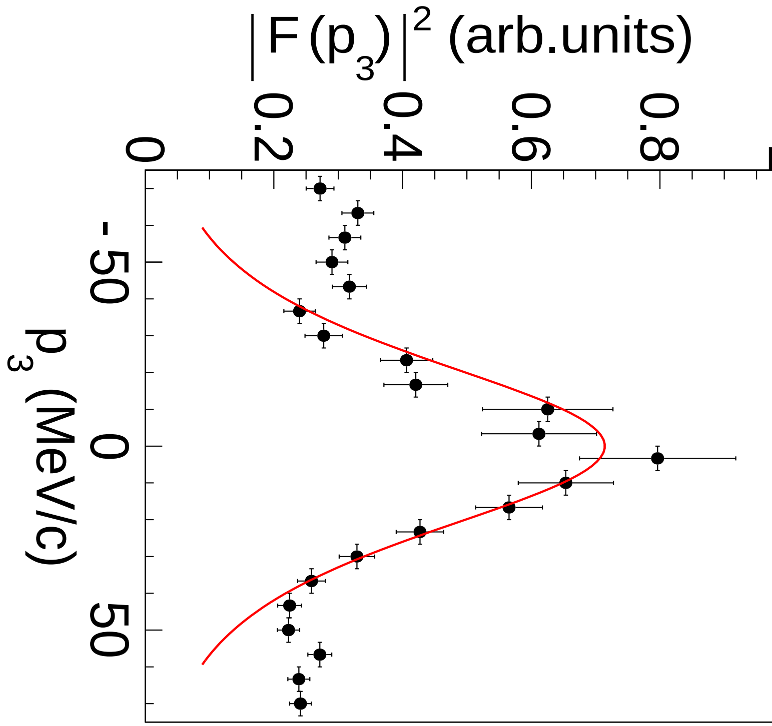


When the breakup is quasi-free, *n* retains the same momentum as inside *d* (adiabatic process). **So *n*-momentum distribution should be the same as in *d***





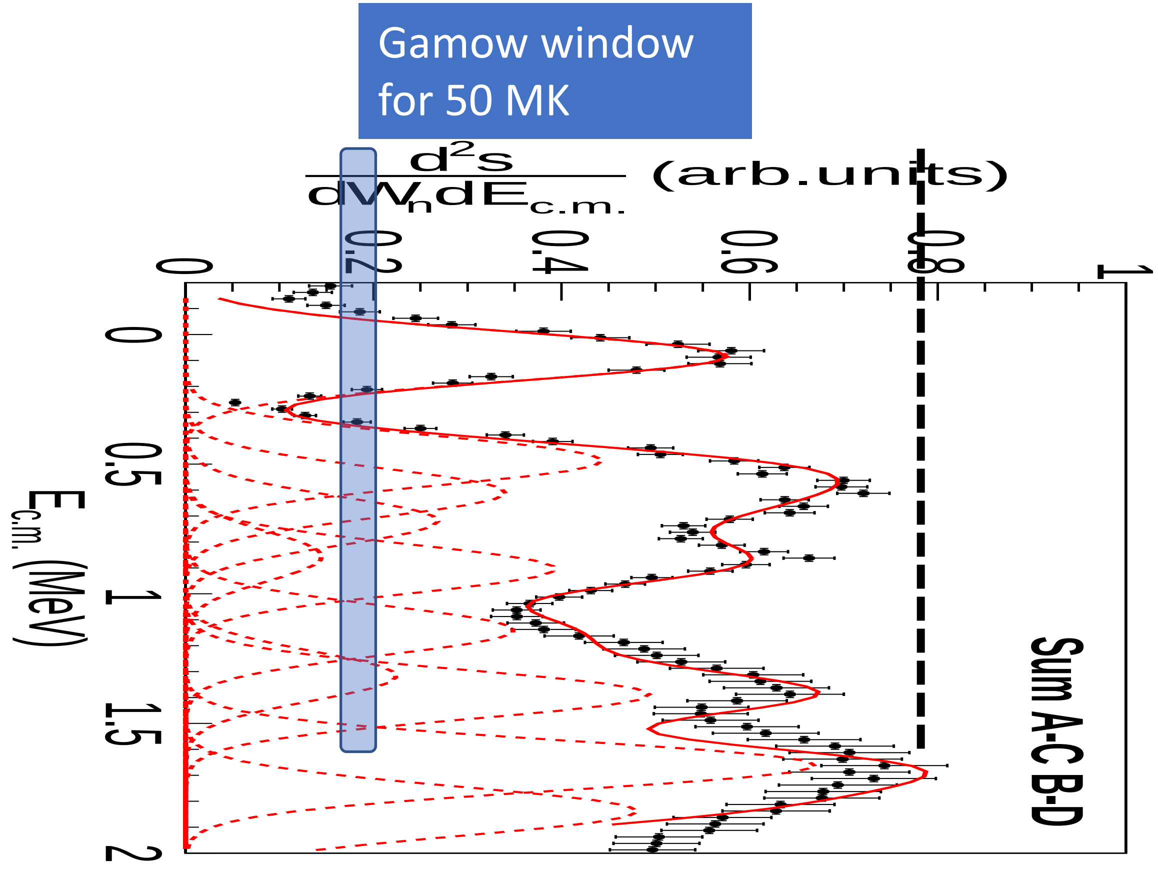
The red curve is the theoretical one: normalization is the only fitting parameter



Extraction of the resonance strengths

Energy in cm (keV) [from STARLIB]	Jpi	Strength (eV) [from STARLIB]	error (eV)	Strength (eV) [from THM]	error (eV)
71.5	2+	2.47E-14	up lim	8.23E-15	up lim
84.3	1-	2.60E-13	up lim	1.67E-14	3.2E-15
193.5	2+	3.74E-07	up lim	2.50E-07	up lim
214.7	3-	1.13E-07	up lim	4.36E-08	up lim
486.74	2+	0.11	0.05	0.107	0.021
609.49	3-	0.275	0.069	0.245	0.054
705.08	1-	0.52	0.13	0.261	0.065
855.85	3-	0.83	0.21	0.61	0.35
903.54*	3-	4.3	0.4	4.20	0.38
1140.88	2+	79	27	73	14
1316.7	2+	137	47	124	28
1388.8*	1-	54	15	61	12

* Normalization strengths



- Following discussion in APJ 708 (2010) 796 the red line is a fit with a sum of Gaussian functions, with fixed energies and fixed widths (from MC). Heights are proportional to strengths
- The most intense resonances in STARLIB were all included in the fit down to about 200 keV

Calculation of the reaction rate

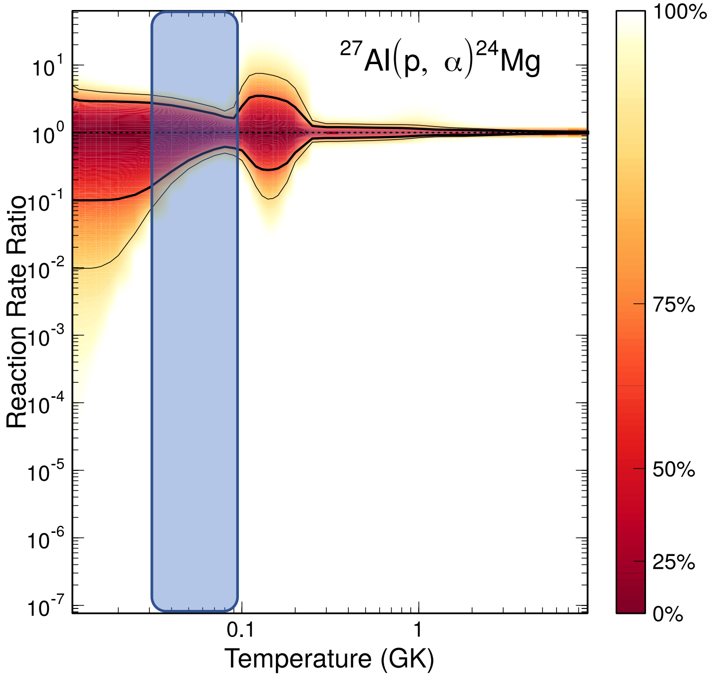
The reaction rate is the main input of astrophysical models. It is the folding of the cross section and of the Maxwell-Boltzmann distribution.

If the cross section is dominated by narrow resonances as in this case, it can be written as

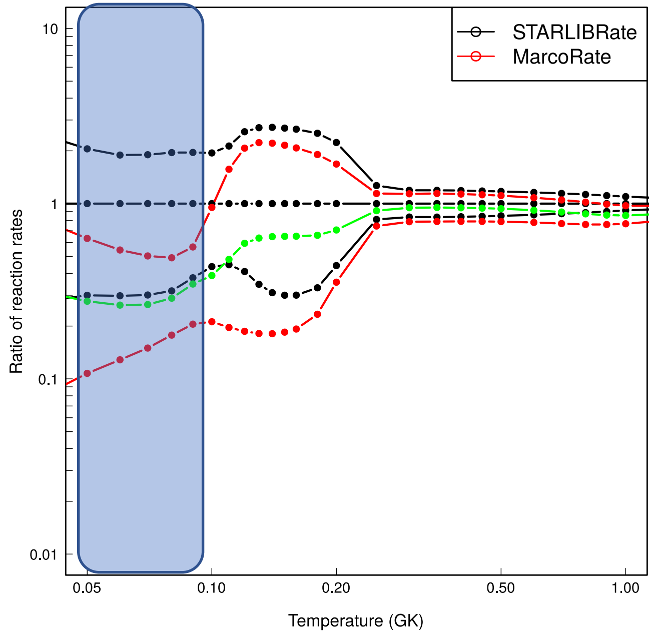
$$N_A\langle\sigma v\rangle = \frac{1.5399\times 10^{11}}{\left(\frac{M_0 M_1}{M_0+M_1}\,T_9\right)^{3/2}}\sum_i (\omega\gamma)_i e^{-11.605\,E_i/T_9}$$

In units of $cm^3 mol^{-1} s^{-1}$.

Therefore, the rate is determined by resonance energies and strengths.



The reaction rate was calculated using **RatesMC**, a MC code to calculate the reaction rate taking lognormal distributions for the measured strengths, and Porter-Thomas distributions in the case only upper limits are available



The green line is the THM recommended rate

The comparison with the results in the literature shows a reduced reaction rate due to the 84 keV resonance

S. Palmerini et al. Eur. Phys. J. Plus (2021) 136: 898
M. La Cognata et al. Phys. Lett. B (2022) 826: 136917

Summary

1. introduction: what is nuclear astrophysics? How to measure nuclear reactions at astrophysical energies

2. Indirect methods: the ANC. Recent results on the $^{3}He(\alpha,\gamma)^{7}Be$ and the $^{6}Li(p,\gamma)^{7}Be$ reactions

3. Indirect methods: the THM. Study of the $^{27}Al(p,\alpha)^{24}Mg$ reaction through the $^{2}H(^{27}Alp,\alpha^{24}Mg)n$ process

4. Concluding: indirect methods are alternative and sometimes unique tools to explore astrophysical energies

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