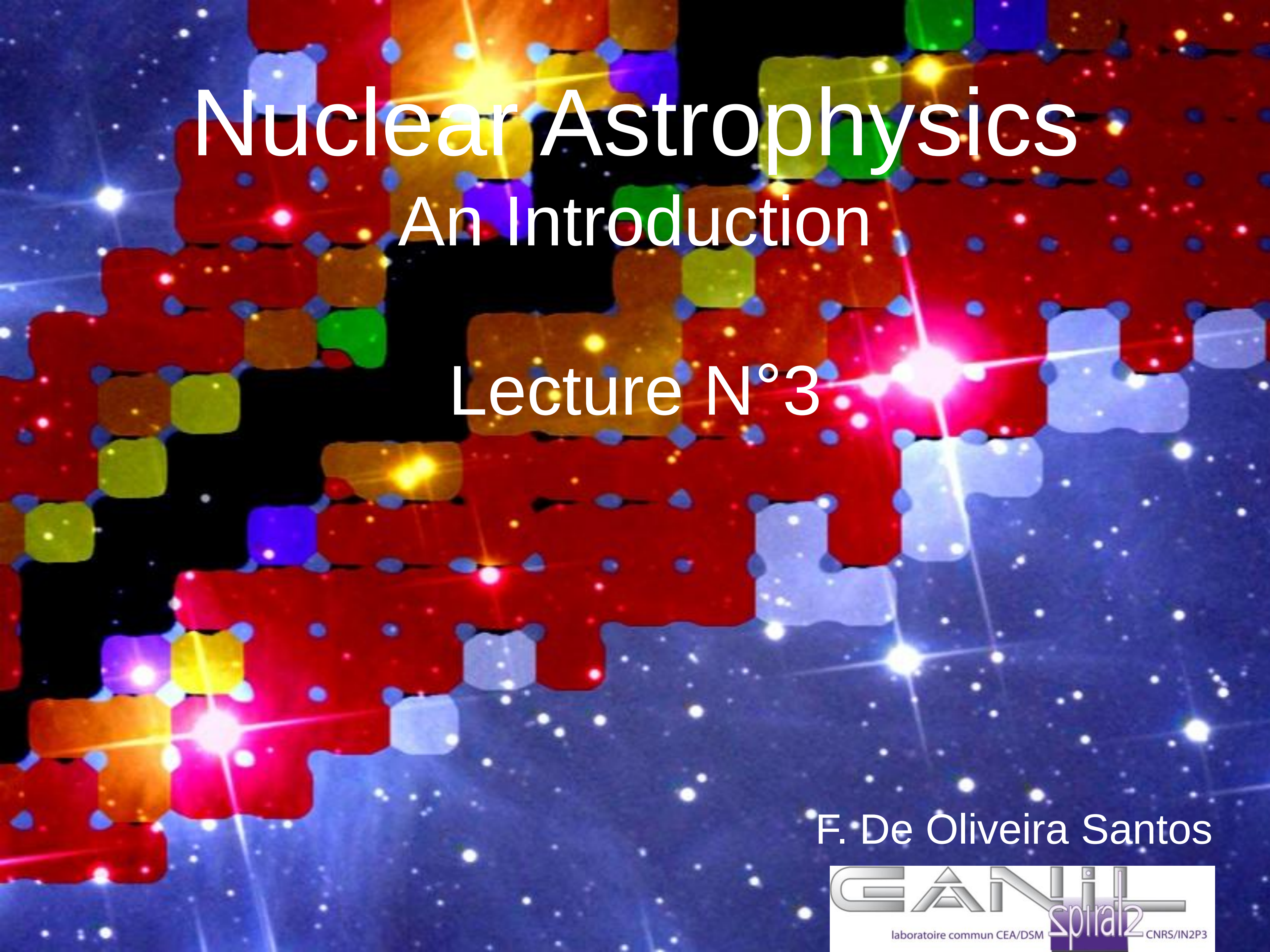


Nuclear Astrophysics

An Introduction

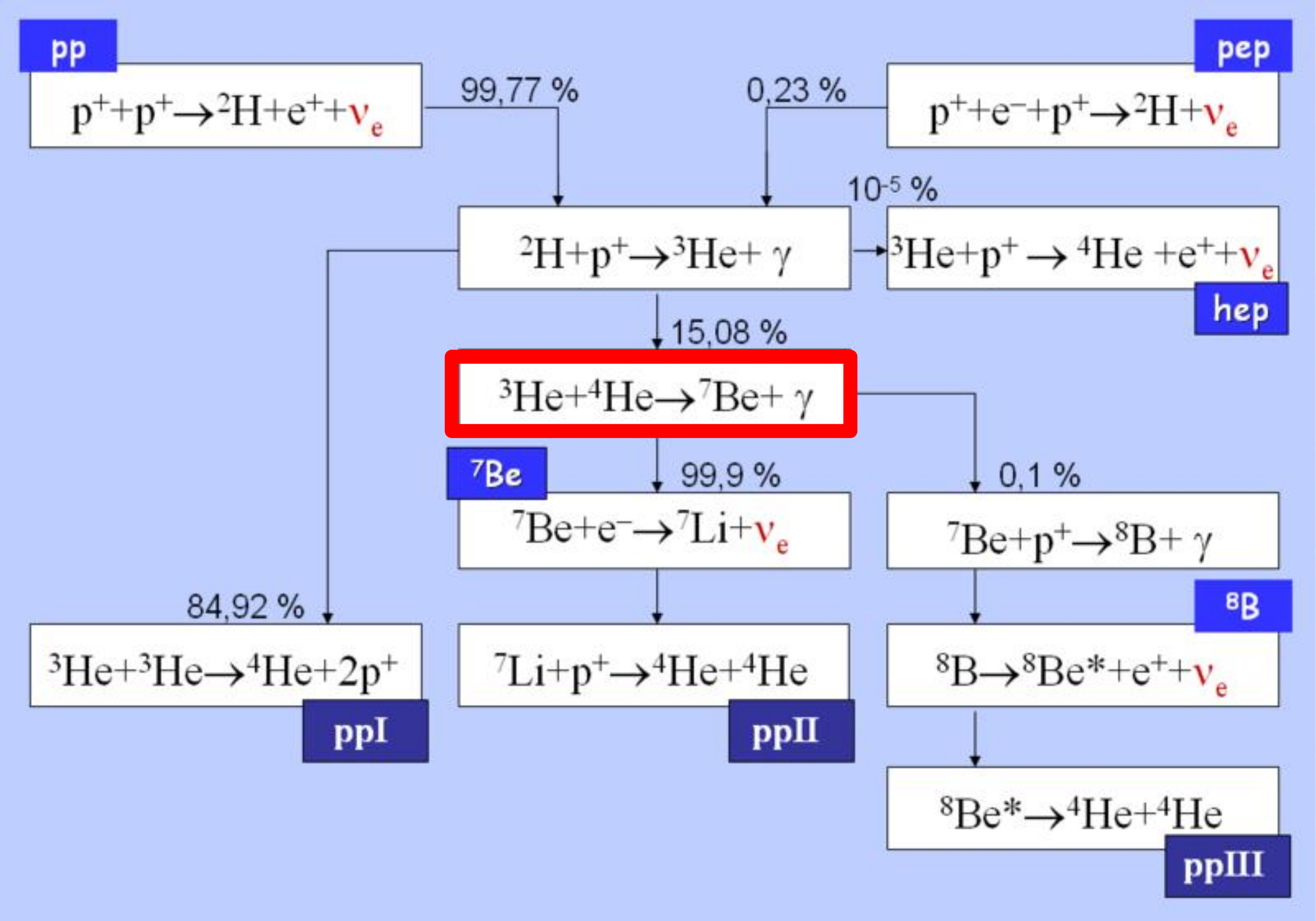
Lecture N°3

F. De Oliveira Santos

laboratoire commun CEA/DSM CNRS/IN2P3

Example 5

Motivation: The solar neutrinos problem



$p^+ + p^+ \rightarrow {}^2H + e^+ + \nu_e$

$p^+ + e^- + p^+ \rightarrow {}^2H + \nu_e$

$^2H + p^+ \rightarrow {}^3He + \gamma$

$^3He + p^+ \rightarrow {}^4He + e^+ + \nu_e$

$^3He + {}^4He \rightarrow {}^7Be + \gamma$

$^7Be + e^- \rightarrow {}^7Li + \nu_e$

$^7Be + p^+ \rightarrow {}^8B + \gamma$

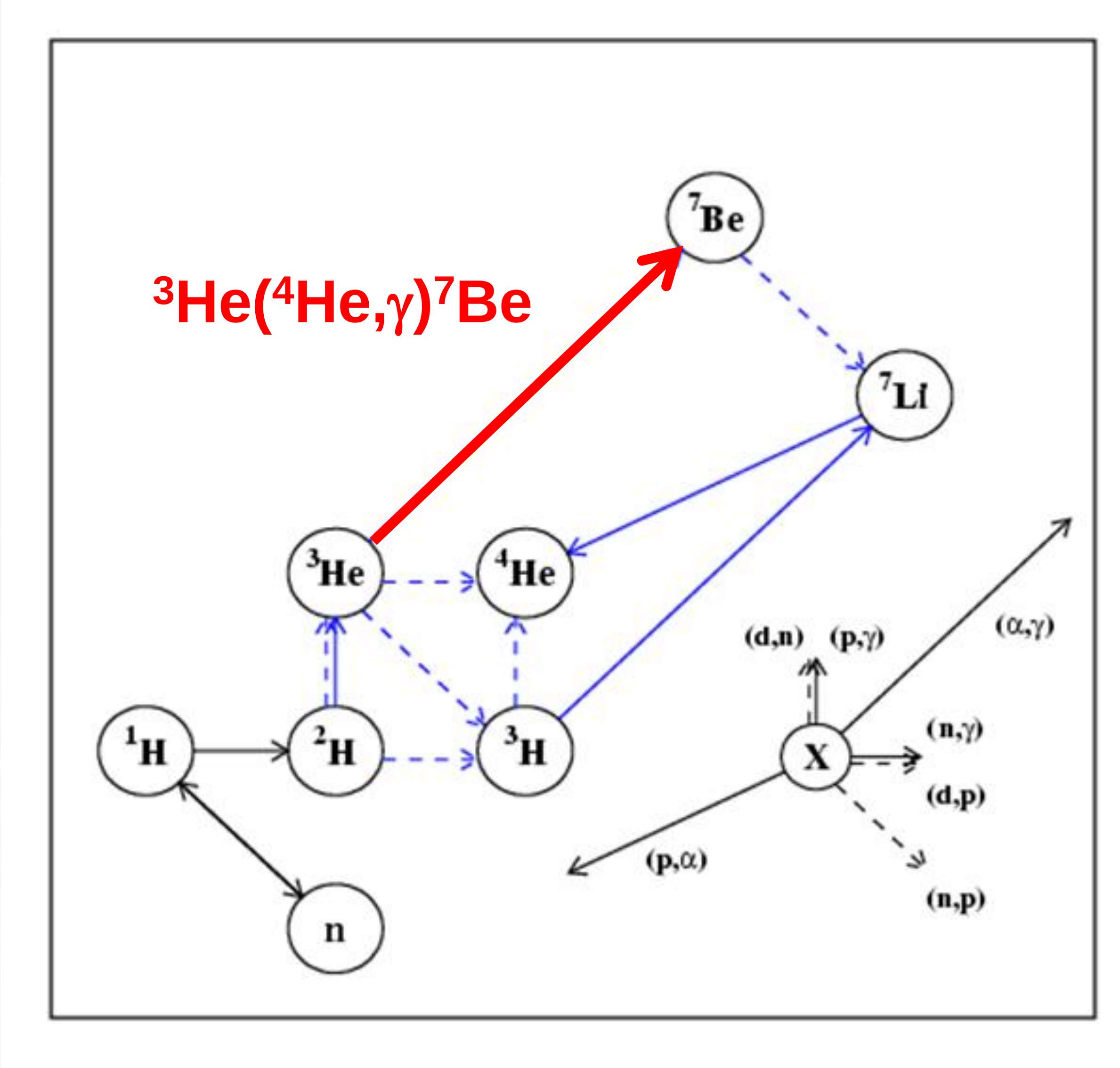
$^3He + {}^3He \rightarrow {}^4He + 2p^+$

$^7Li + p^+ \rightarrow {}^4He + {}^4He$

$^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

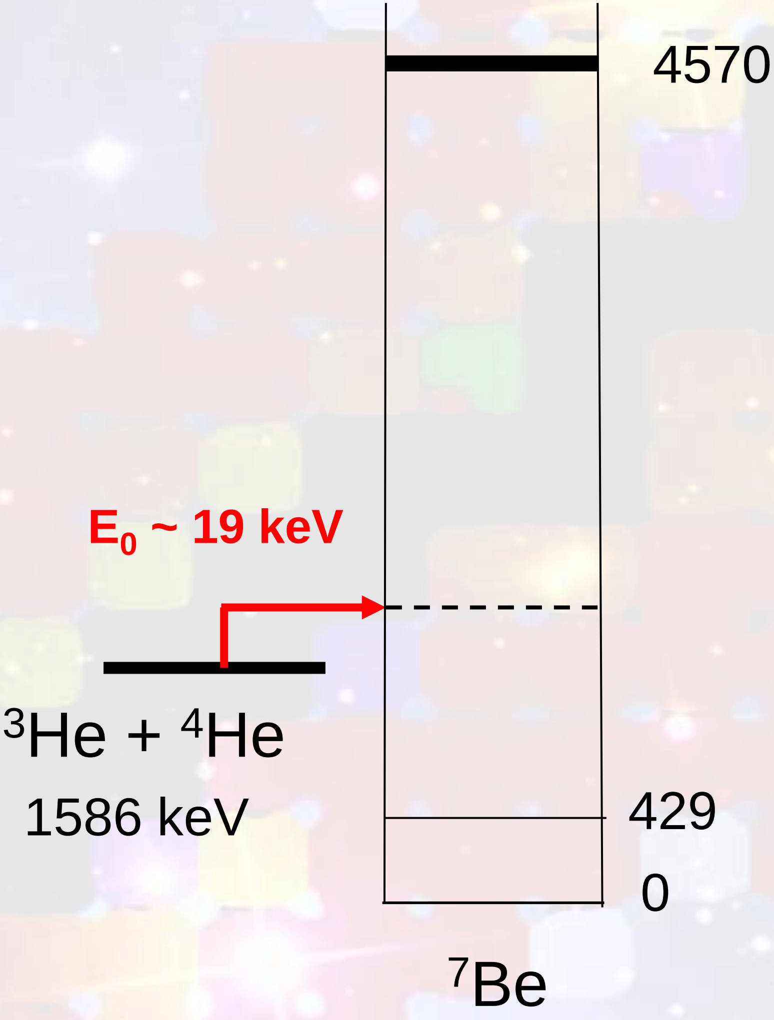
$^8Be^* \rightarrow {}^4He + {}^4He$

Another motivation: Primordial abundance of ^{7}Li



^{3}He(^{4}He,γ)^{7}Be

"Theoretical" investigations of $^3He(\alpha,\gamma)^7Be$



4570

E_0 ~ 19 keV

$^3He + ^4He$

1586 keV

429

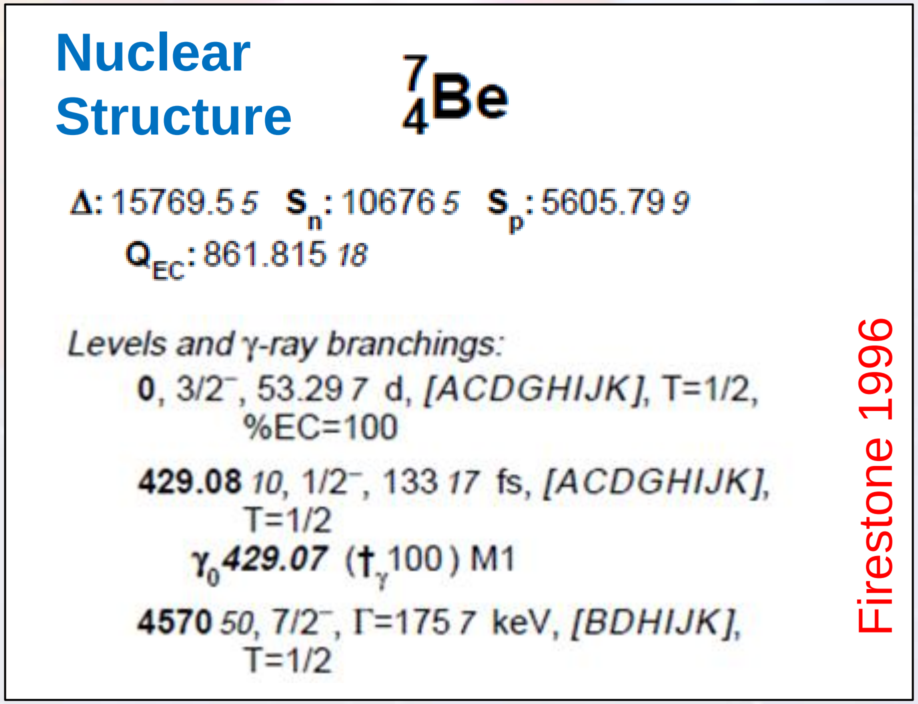
0

^7Be

- No resonance predicted
- Tail of the 4570 keV resonance?

Gamow Peak

T6 = 15 **E_0 ~ 19 keV**



Nuclear Structure ^7_4Be

Δ: 15769.5 *5* **S_n**: 10676 *5* **S_p**: 5605.79 *9*
Q_{EC}: 861.815 *18*

Levels and γ-ray branchings:

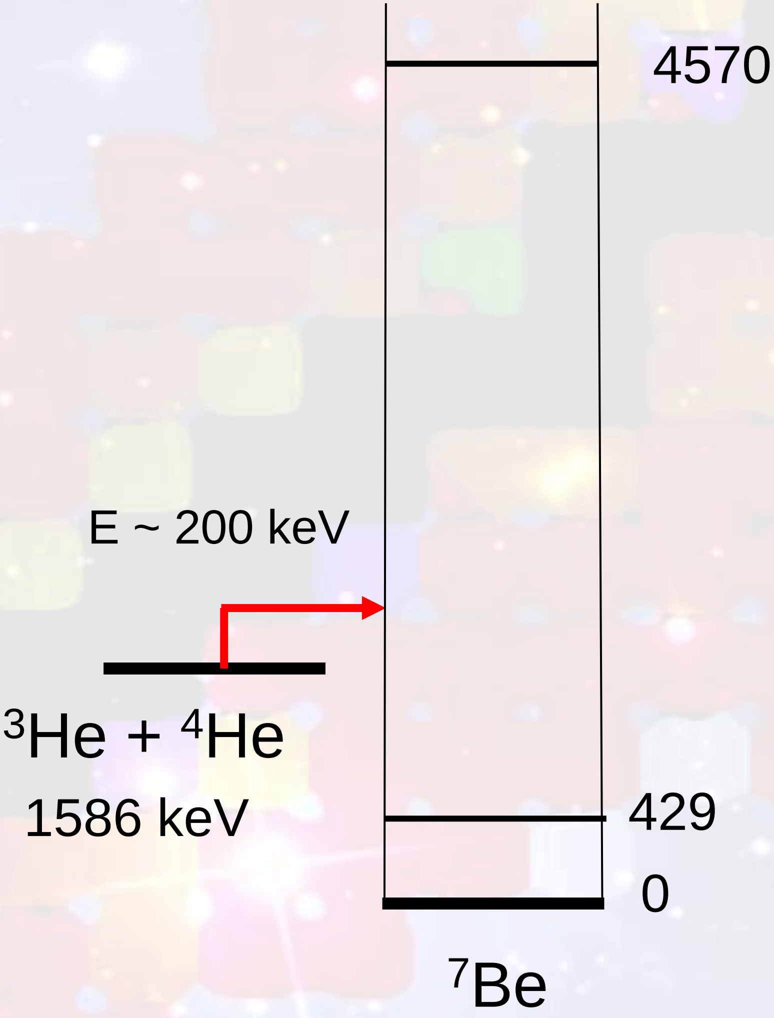
0, $3/2^-$, 53.29 *7* d, *[ACDGHIJK]*, T=1/2, %EC=100

429.08 *10*, $1/2^-$, 133 *17* fs, *[ACDGHIJK]*, T=1/2
γ_0 *429.07* (I_γ100) M1

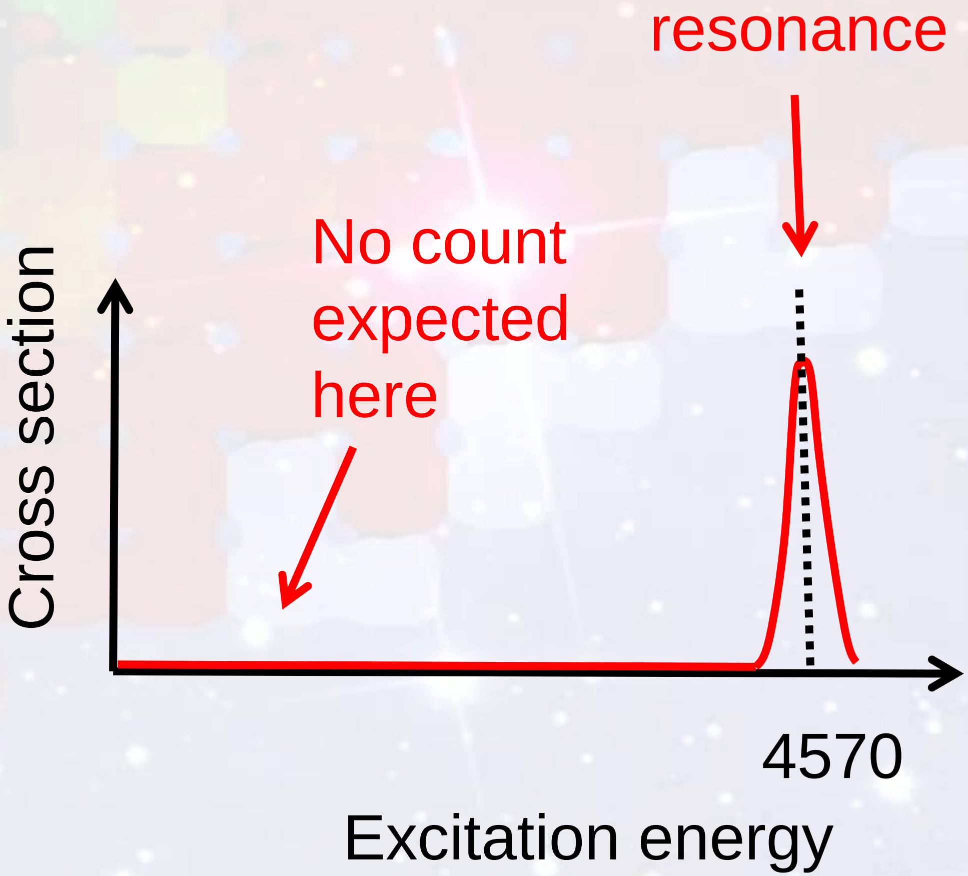
4570 *50*, $7/2^-$, Γ=175 *7* keV, *[BDHIJK]*, T=1/2

Firestone 1996

“Theoretical” investigations of $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$

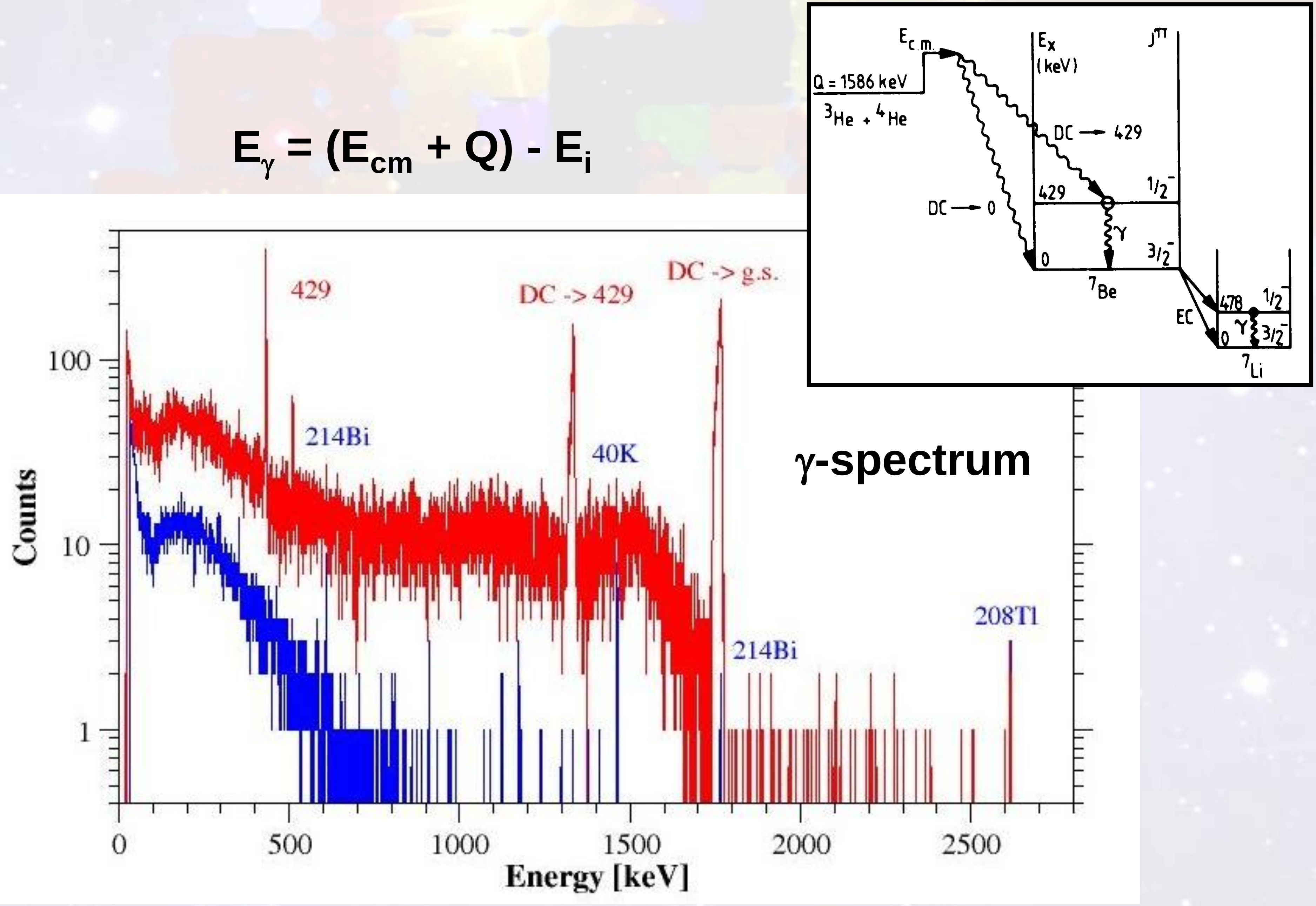


Compound nucleus model



But γ-rays are measured!

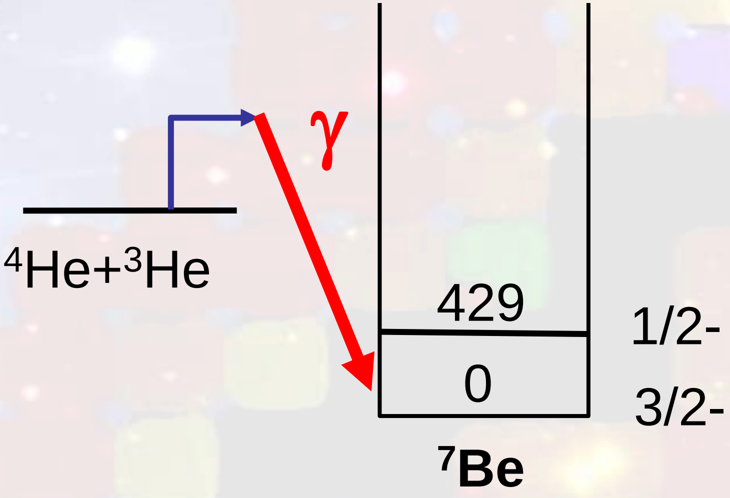
$E_\gamma = (E_{cm} + Q) - E_i$



γ-spectrum

Direct (non-resonant) radiative capture reaction

(not to be confused with Direct Measurement)



$$\sigma_{DC}(E) \propto \left| \left\langle {}^7\mathrm{Be} \right| H_\gamma \left| {}^4\mathrm{He} + {}^3\mathrm{He} \right\rangle \right|^2$$

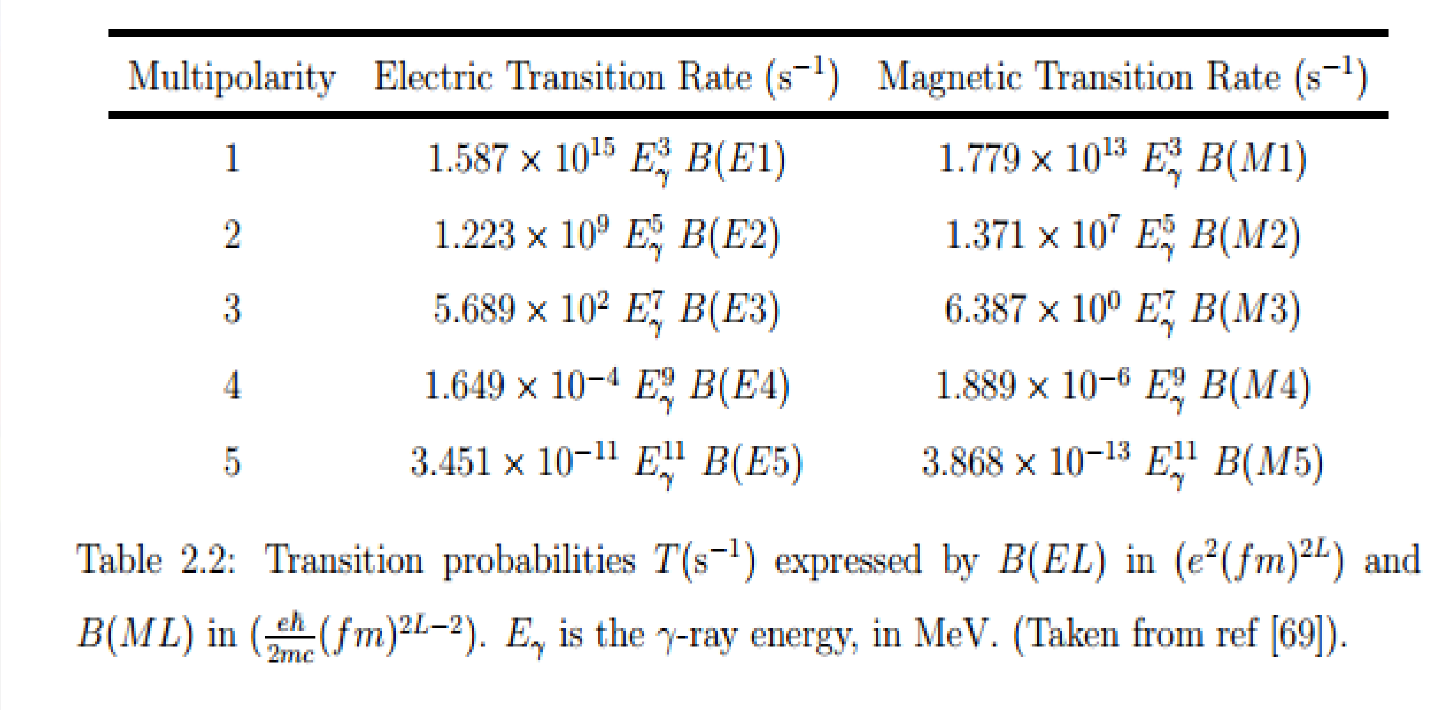
Final bound state wave function

Electromagnetic operator describing the transition

Initial continuum wave function

Can occur at all projectile energies.

Smooth energy dependence of cross section.



Multipolarity	Electric Transition Rate (s^{-1})	Magnetic Transition Rate (s^{-1})
1	$1.587 \times 10^{15}\ E_\gamma^3\ B(E1)$	$1.779 \times 10^{13}\ E_\gamma^3\ B(M1)$
2	$1.223 \times 10^{9}\ E_\gamma^5\ B(E2)$	$1.371 \times 10^{7}\ E_\gamma^5\ B(M2)$
3	$5.689 \times 10^{2}\ E_\gamma^7\ B(E3)$	$6.387 \times 10^{0}\ E_\gamma^7\ B(M3)$
4	$1.649 \times 10^{-4}\ E_\gamma^9\ B(E4)$	$1.889 \times 10^{-6}\ E_\gamma^9\ B(M4)$
5	$3.451 \times 10^{-11}\ E_\gamma^{11}\ B(E5)$	$3.868 \times 10^{-13}\ E_\gamma^{11}\ B(M5)$

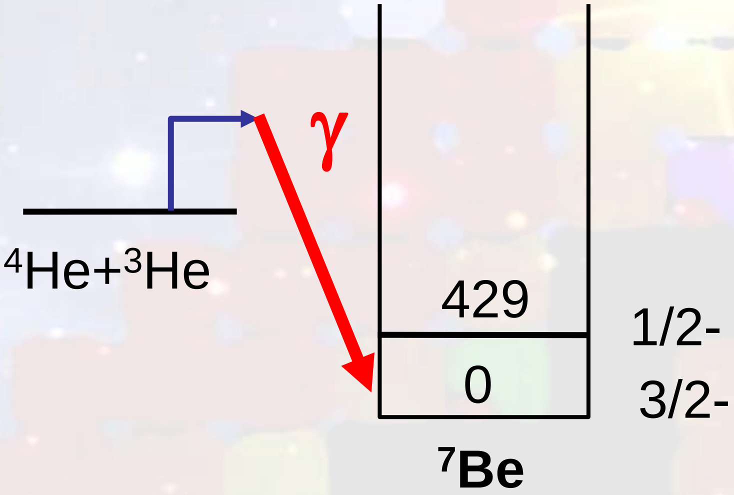
Table 2.2: Transition probabilities $T(s^{-1})$ expressed by $B(EL)$ in $(e^2(fm)^{2L})$ and $B(ML)$ in $(\frac{e\hbar}{2mc}(fm)^{2L-2})$. E_γ is the γ-ray energy, in MeV. (Taken from ref [69]).

E_γ = 1 MeV

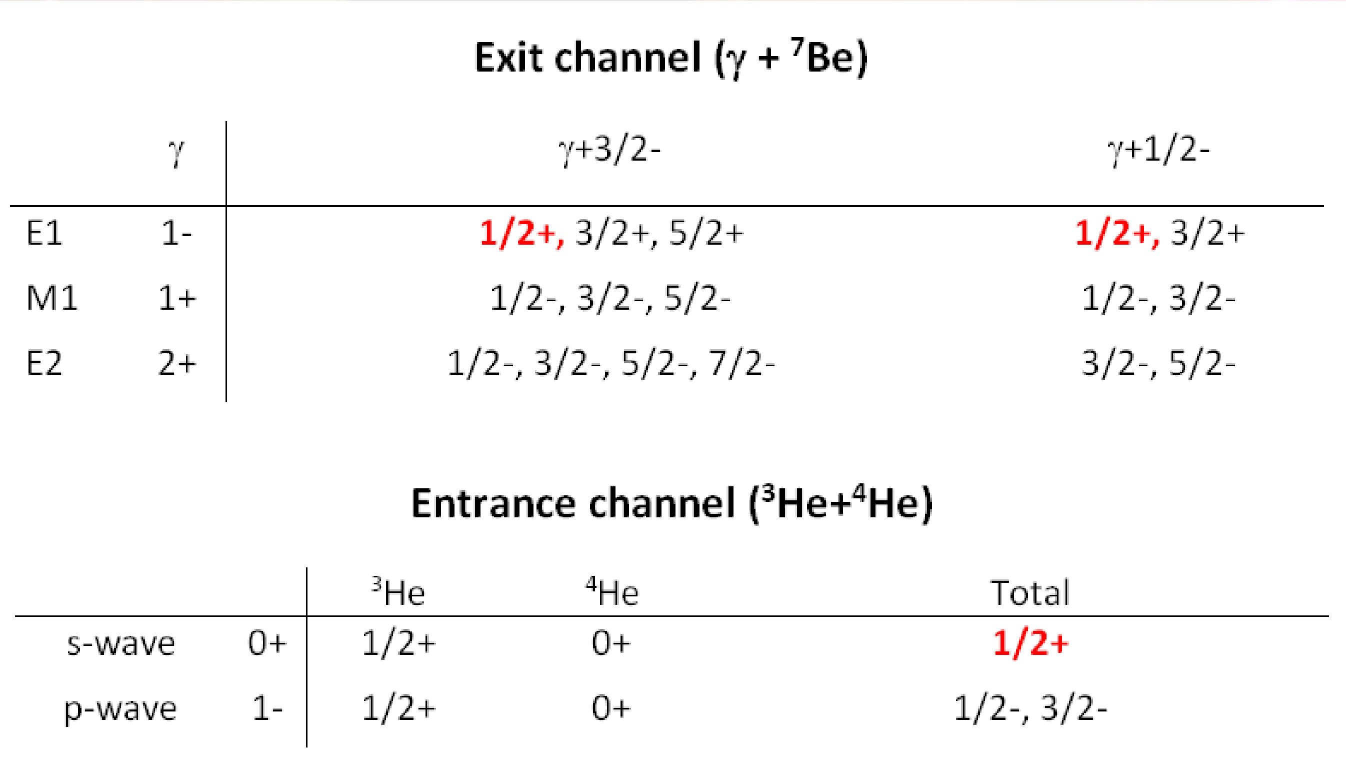
E1	**10^{-14} s**
E2	1.3×10^{-8} s
E3	2.9×10^{-2} s

M1	**3.2×10^{-14} s**
M2	4.5×10^{-8} s
M3	10^{-1} s

Angular momentum matching



$^4\text{He} + {}^3\text{He} \rightarrow \gamma + {}^7\text{Be}$



Exit channel (γ + ^{7}Be)

	γ	γ+3/2-	γ+1/2-
E1	1-	**1/2+,** 3/2+, 5/2+	**1/2+,** 3/2+
M1	1+	1/2-, 3/2-, 5/2-	1/2-, 3/2-
E2	2+	1/2-, 3/2-, 5/2-, 7/2-	3/2-, 5/2-

Entrance channel (^{3}He+^{4}He)

		^{3}He	^{4}He	Total
s-wave	0+	1/2+	0+	**1/2+**
p-wave	1-	1/2+	0+	1/2-, 3/2-

For the two final states, the most intense contribution is a s-wave capture coupled to an E1 γ-transition.

Direct non-resonant radiative capture reaction

Expanding the electrostatic potential in spherical harmonics

$$\varphi(\mathbf{r}) = \frac{Z_p e}{|\mathbf{r}-\mathbf{r}_p|} = \sum_{\lambda\mu} \frac{4\pi Z_p e}{2\lambda+1} Y^*_{\lambda\mu}(\hat{\mathbf{r}}_p)\, Y_{\lambda\mu}(\hat{\mathbf{r}}) \begin{cases} r_p^{-\lambda-1} r^{\lambda} & r_p > r \\ r_p^{\lambda} r^{-\lambda-1} & r_p < r \end{cases}$$

Bohr & Mottelson vol I

Operators for electric transitions of multipolarity λ

$$\mathcal{O}_{E\lambda\mu} = e_\lambda\, r^\lambda Y_{\lambda\mu}(\hat{\mathbf{r}})$$

$$\sigma^{E1}_{DC}(E) \propto \frac{1}{E}\ \omega\ \ S\ \ E_\gamma^3\ \left|\int \varphi_{n_f \ell_f}(r)\ \ r\ \ \chi(E,r)\, dr\right|^2$$

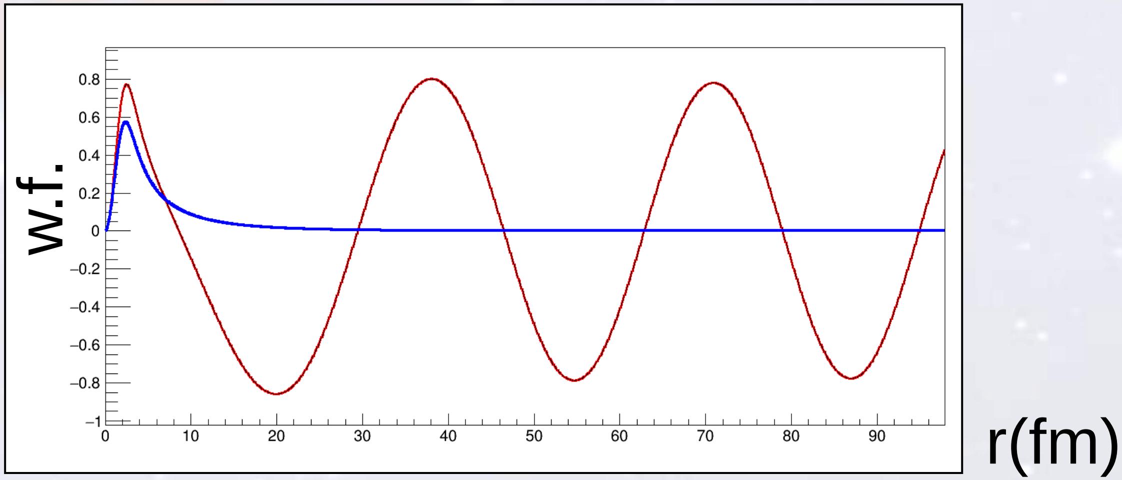
Spectroscopic factor

Final bound state wave function

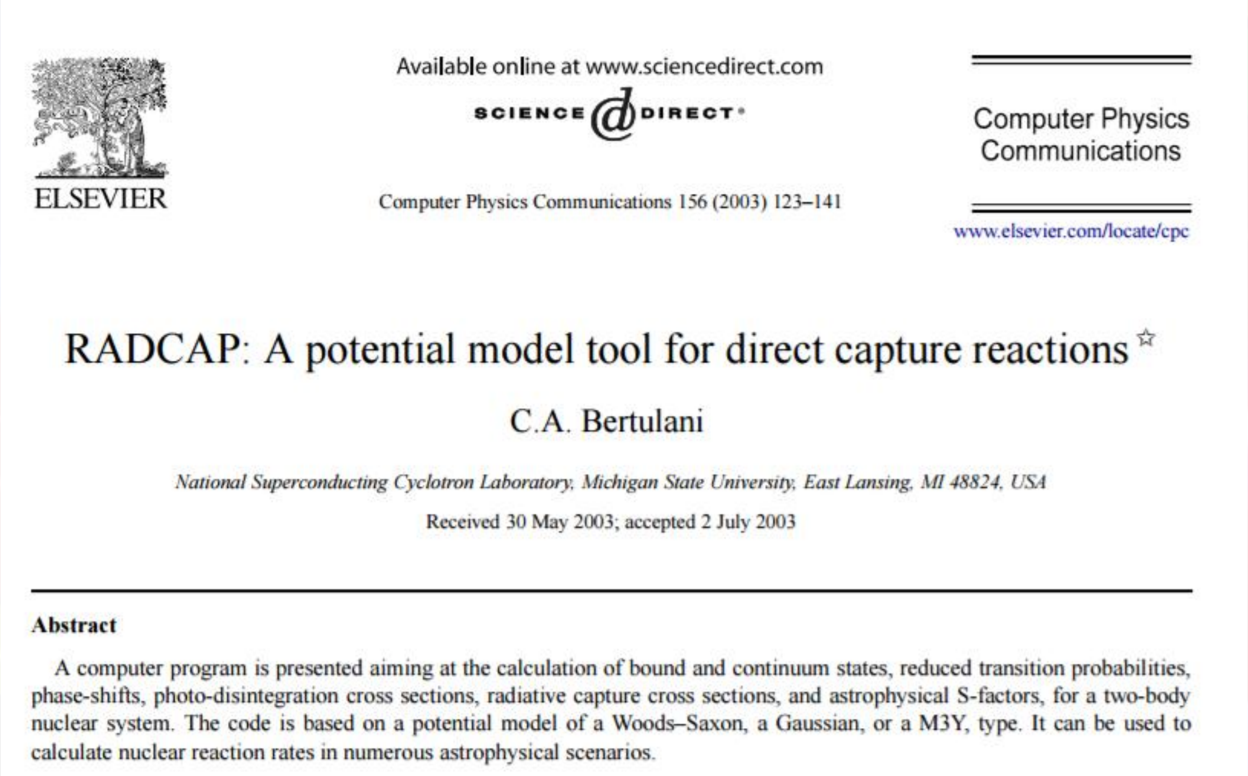
Initial continuum wave function

^{3}He(α,γ)^{7}Be

$$S = \left|\left\langle {}^7\mathrm{Be} \middle| {}^4\mathrm{He} + {}^3\mathrm{He} \right\rangle\right|^2$$



RADCAP



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Computer Physics Communications 156 (2003) 123–141

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RADCAP: A potential model tool for direct capture reactions ☆

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Received 30 May 2003; accepted 2 July 2003

Abstract

A computer program is presented aiming at the calculation of bound and continuum states, reduced transition probabilities, phase-shifts, photo-disintegration cross sections, radiative capture cross sections, and astrophysical S-factors, for a two-body nuclear system. The code is based on a potential model of a Woods–Saxon, a Gaussian, or a M3Y, type. It can be used to calculate nuclear reaction rates in numerous astrophysical scenarios.

Codes:

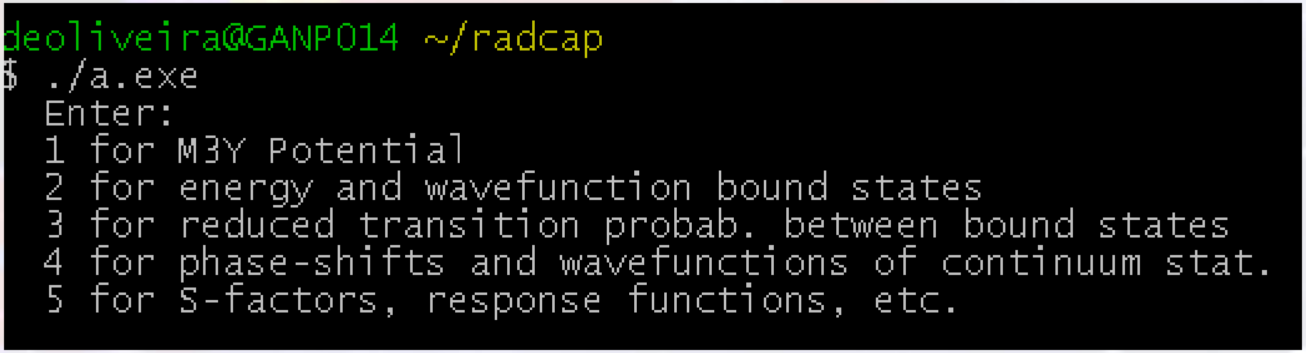
TEDCA

https://nucastro.org/codes.html#TEDCA

DIRCAD

RADCAP

http://cpc.cs.qub.ac.uk/summaries/ADSH_v1_0.html



```
deoliveira@GANP014 ~/radcap
$ ./a.exe
  Enter:
  1 for M3Y Potential
  2 for energy and wavefunction bound states
  3 for reduced transition probab. between bound states
  4 for phase-shifts and wavefunctions of continuum stat.
  5 for S-factors, response functions, etc.
```

It requires, at least, to know the spectroscopic factors

$$S = \left| \left\langle {}^{7}\mathrm{Be} \middle| {}^{4}\mathrm{He} + {}^{3}\mathrm{He} \right\rangle \right|^{2}$$

Estimation of the cross section / counts

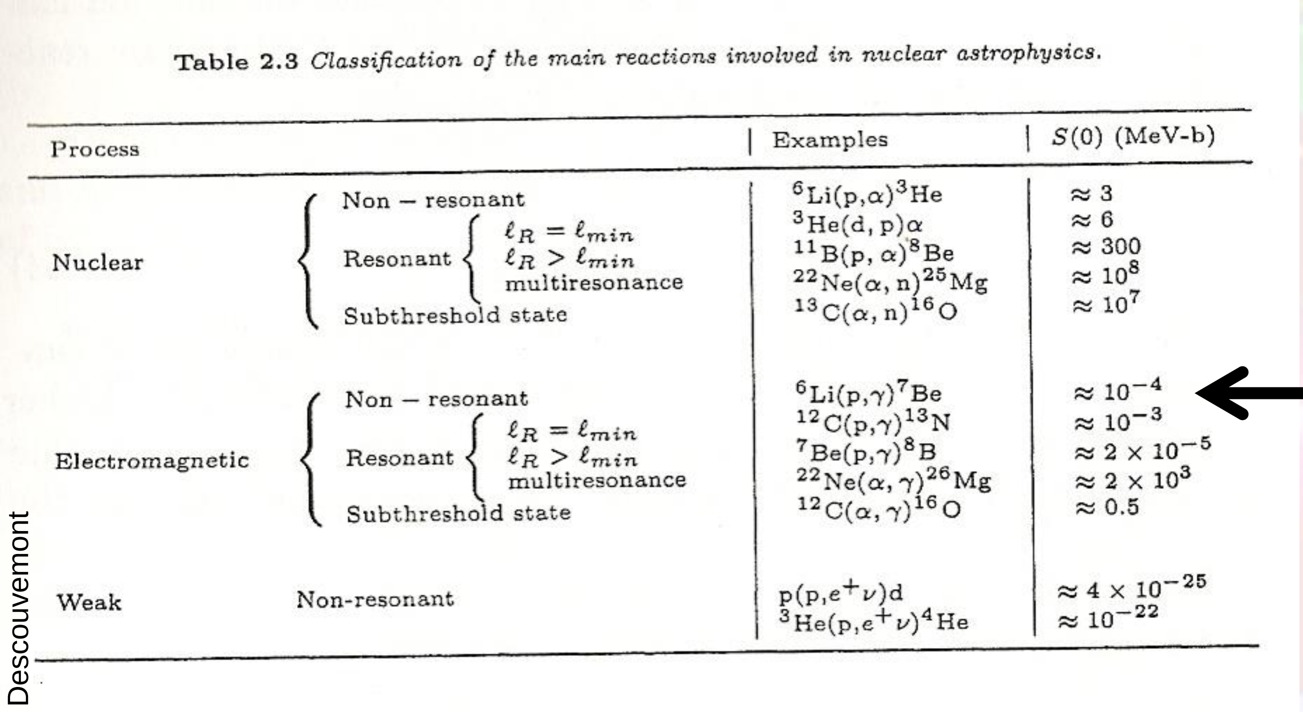


Table 2.3 *Classification of the main reactions involved in nuclear astrophysics.*

Process			Examples	$S(0)$ (MeV-b)
Nuclear	Non – resonant		^{6}Li(p,α)^{3}He	≈ 3
	Resonant	$\ell_R = \ell_{min}$	^{3}He(d, p)α	≈ 6
		$\ell_R > \ell_{min}$	^{11}B(p, α)^{8}Be	≈ 300
		multiresonance	^{22}Ne(α, n)^{25}Mg	$\approx 10^{8}$
	Subthreshold state		^{13}C(α, n)^{16}O	$\approx 10^{7}$
Electromagnetic	Non – resonant		^{6}Li(p,γ)^{7}Be	$\approx 10^{-4}$
	Resonant	$\ell_R = \ell_{min}$	^{12}C(p,γ)^{13}N	$\approx 10^{-3}$
		$\ell_R > \ell_{min}$	^{7}Be(p,γ)^{8}B	$\approx 2 \times 10^{-5}$
		multiresonance	^{22}Ne(α, γ)^{26}Mg	$\approx 2 \times 10^{3}$
	Subthreshold state		^{12}C(α, γ)^{16}O	≈ 0.5
Weak	Non-resonant		p(p,e$^{+}\nu$)d	$\approx 4 \times 10^{-25}$
			^{3}He(p,e$^{+}\nu$)^{4}He	$\approx 10^{-22}$

Theoretical Models for Nuclear Astrphysics – P. Descouvemont

^{3}He(α,γ)^{7}Be

← S(0) ~ 0.1 keV barn

$$\sigma(E) \equiv \frac{S(E)}{E} \exp\left(-2\pi\eta\right)$$

$$2\pi\eta = 31.29 Z_1 Z_2 \left(\frac{\mu}{E}\right)^{1/2}$$

(E en keV)

σ (17 keV) = 2 x 10^{-19} b

$N_{reactions}$ = N_{inc} N_{target} $\sigma(E)$

1 mAe N_{inc} (^{3}He) = 3 x 10^{15} pps

N_{target} ~ 10^{20} at/cm²

$N_{reactions}$ = 2 / year

Not possible to measure directly at E0

Cross section measurement requirements

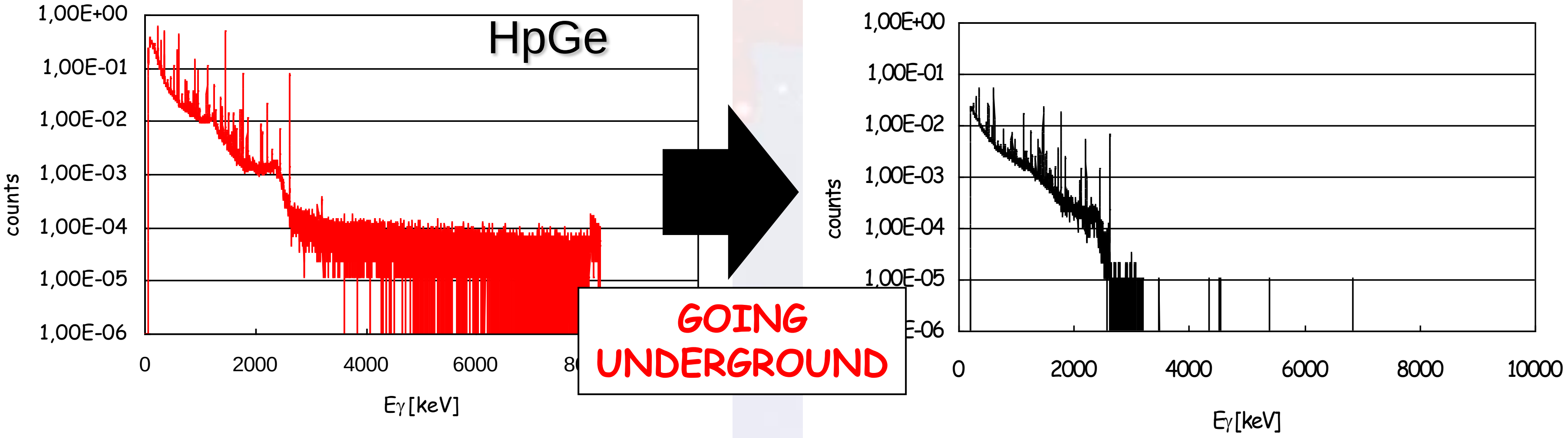
$$R_{lab} > \underbrace{B_{cosm} + B_{env}} + B_{beam\ induced}$$

Environmental radioactivity has to be considered (shielding)
+ intrinsic detector bck

Beam induced bck from impurities in beam & targets → high purity and detector techniques (coincidence)

3MeV < E_γ < 8MeV: **0.5 Counts/s**

0.0002 Counts/s



GOING UNDERGROUND

H. Costantini & http://luna.lngs.infn.it/

Exercise: Lowest accessible energy

If R_{lab} > 0.0002 Counts/s

Lowest accessible energy? $^3He(\alpha,\gamma)^7Be$

0.25 mAe of ^4He ⇒ N_{inc} (^3He) = 0.75×10^{15} pps

$N_{target} \sim 10^{18}$ at/cm²

S(E=0) ~ 0.1 keV barn

γ Detection efficiency ~ 0.004

Solution: Lowest accessible energy

$$0.0002 = 0.004 \text{ x } N_{inc} \text{ x } N_{target} \text{ x } \sigma$$

⬇

$\sigma = 6.7 \text{ x } 10^{-11}$ barns

⬇

$$\sigma(E) = \frac{0.1}{E} \exp(-2\pi\,\eta) = 6.7 \text{ x } 10^{-11}$$

$$2\pi\eta = 31.29 Z_1 Z_2 \left(\frac{\mu}{E}\right)^{1/2} = 163.9 \text{ x } E^{-0.5}$$

⬇

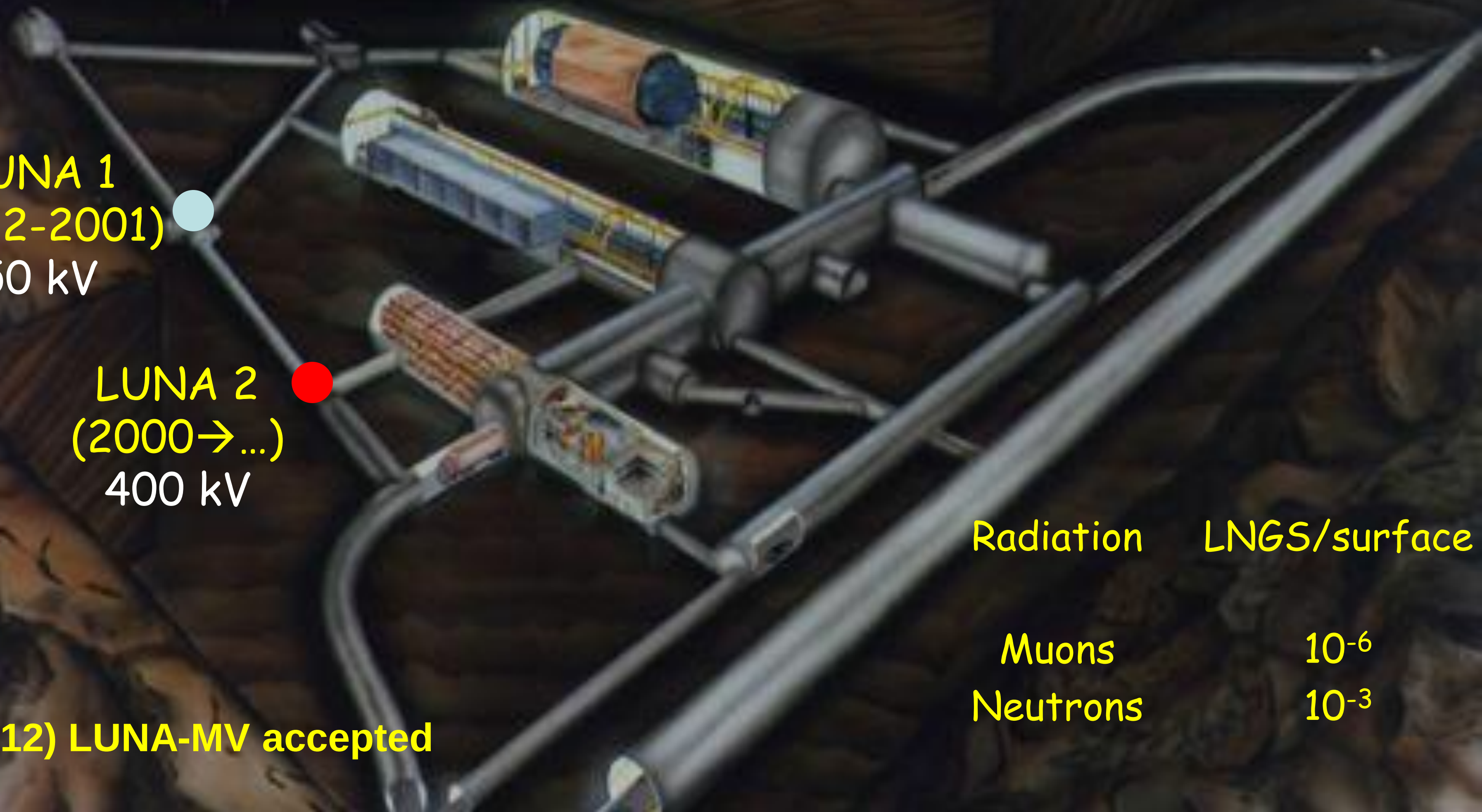
E ~ 100 keV

Direct measurement at LUNA

Laboratory for Underground Nuclear Astrophysics

Gran Sasso

(shielding ≡ 4000 m water equivalent)



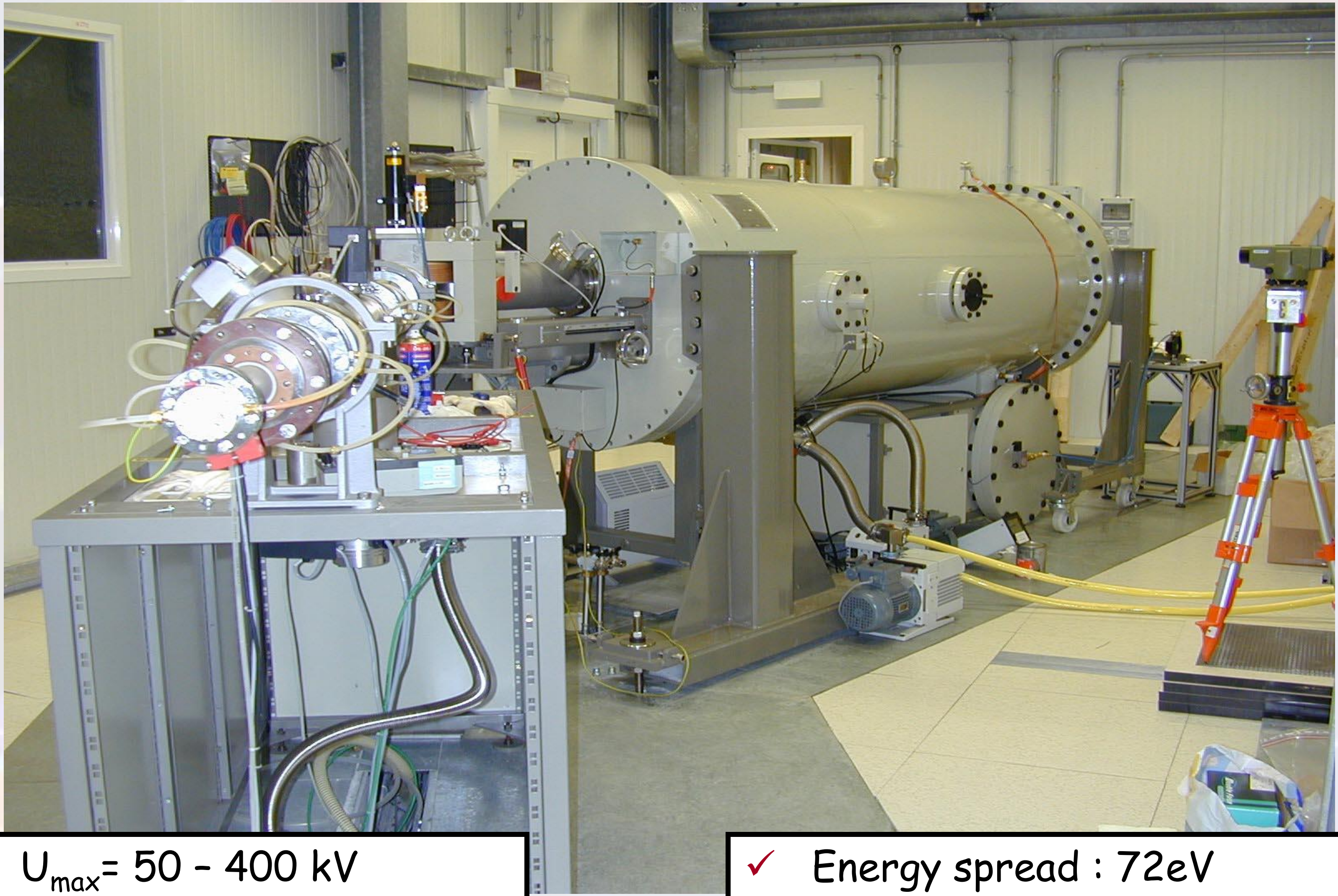
LUNA 1
(1992-2001)
50 kV

LUNA 2
(2000→…)
400 kV

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

(2012) LUNA-MV accepted

LUNAII



- ✓ U_{max}= 50 – 400 kV
- ✓ $I \sim 500\ \mu A$ for protons

  $I \sim 250\ \mu A$ for alphas

- ✓ Energy spread : 72eV
- ✓ Total uncertainty is ±300 eV

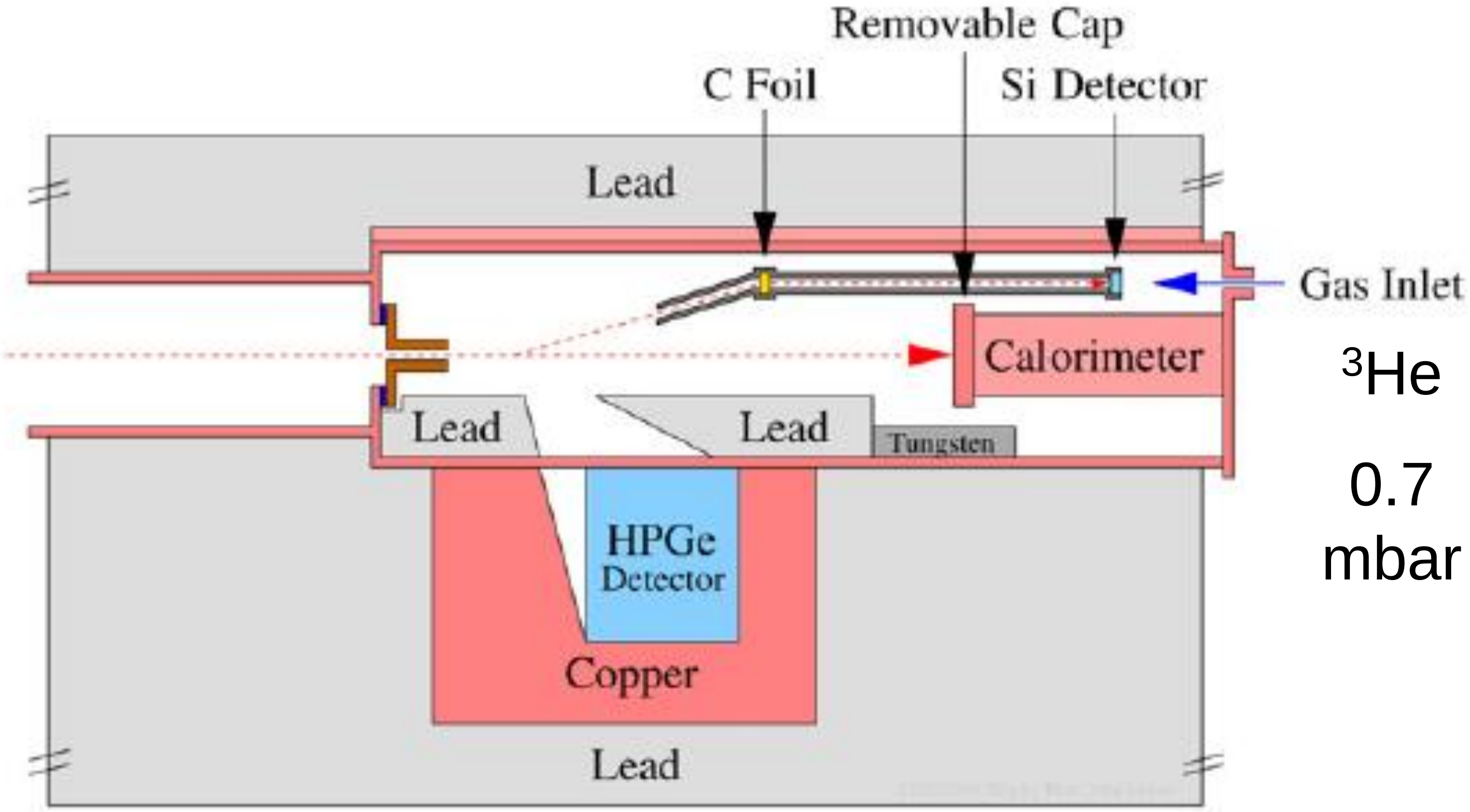
  between $E_p = 100 \div 400$keV

H. Costantini & http://luna.lngs.infn.it/

Direct Measurement of ^{3}He(α,γ)^{7}Be

Beam

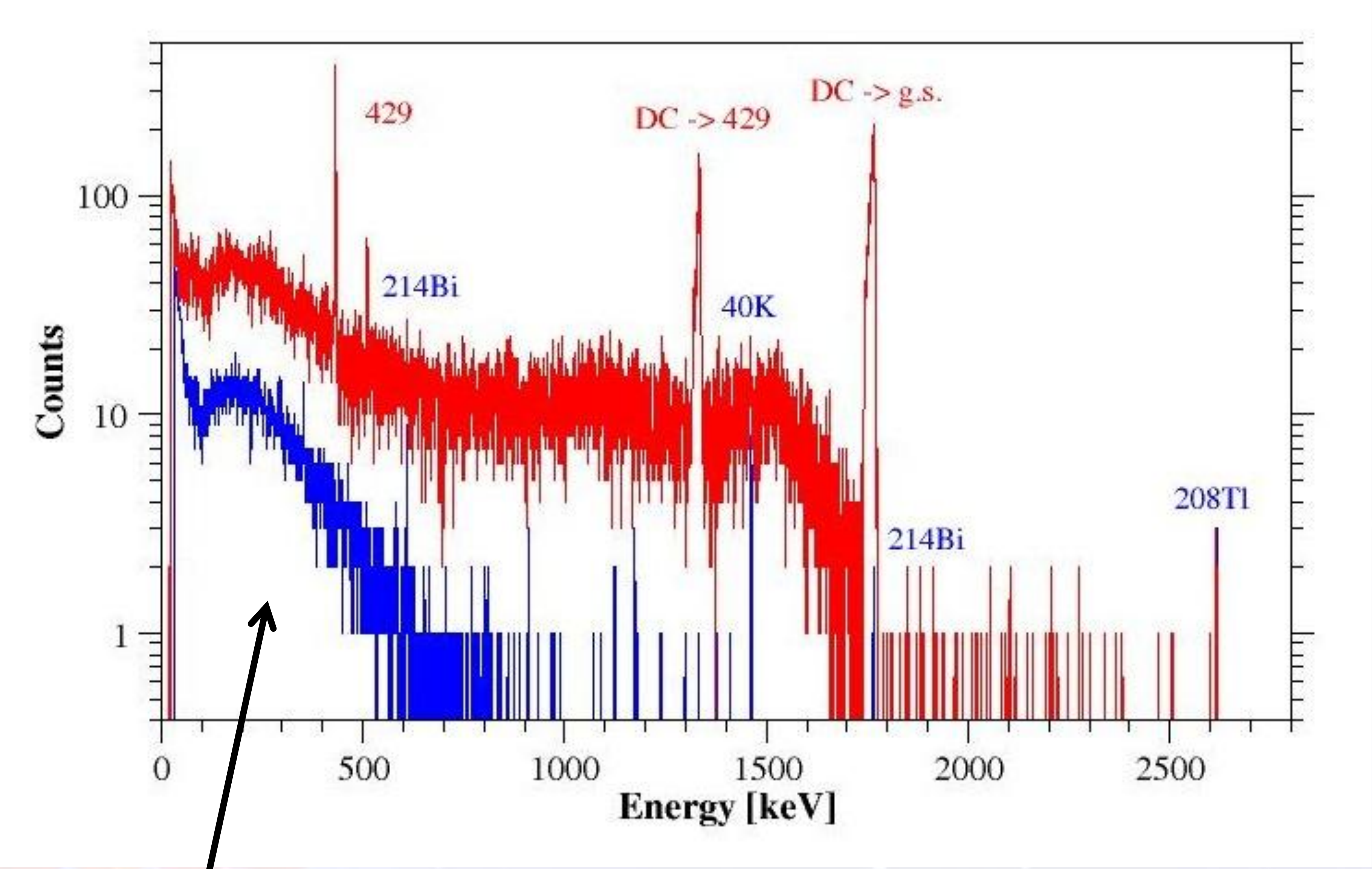
^{4}He



^{3}He

0.7 mbar

H. Costantini et al. / Nuclear Physics A 814 (2008) 144–158

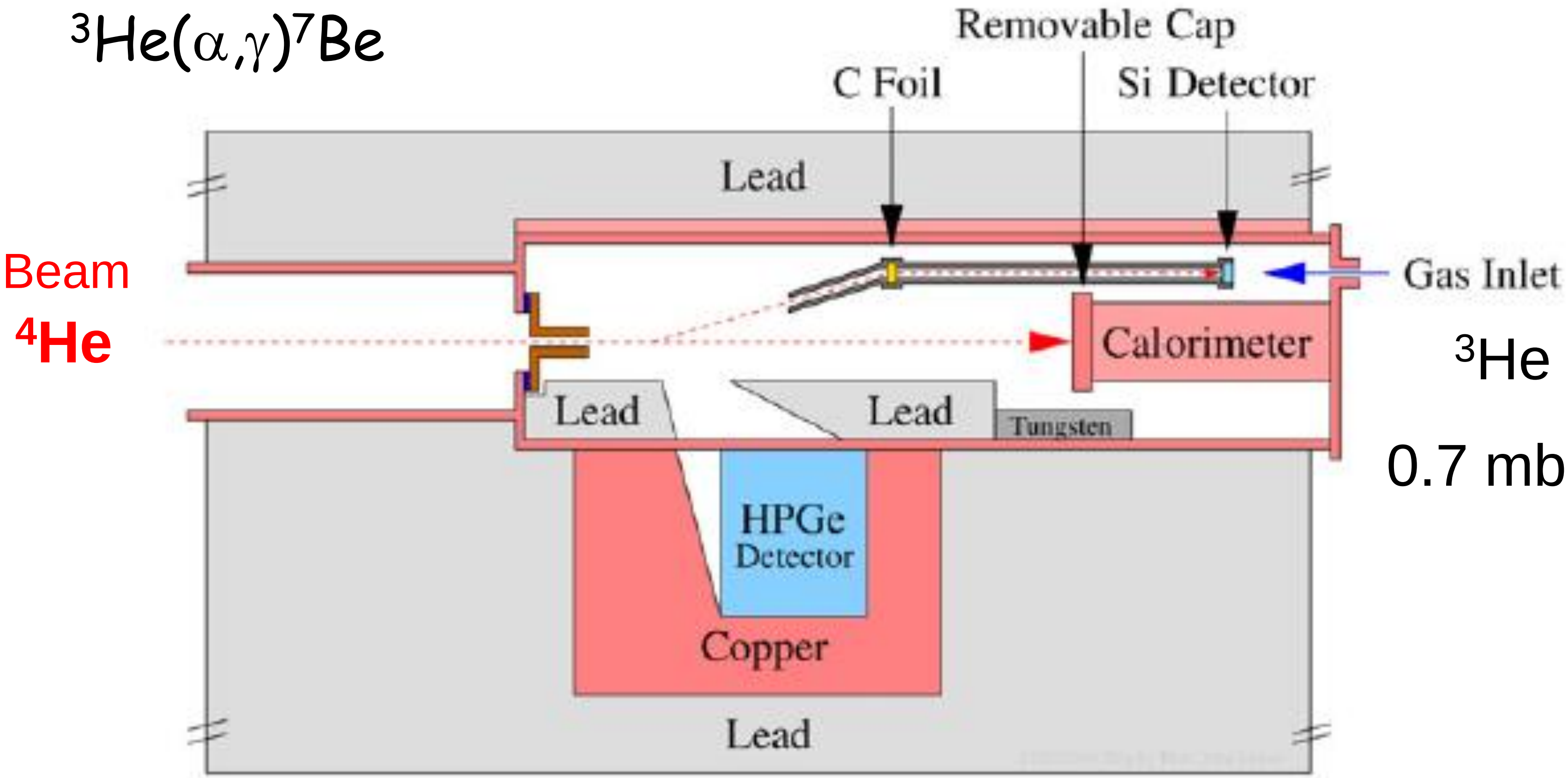

429
DC -> 429
DC -> g.s.
214Bi
40K
214Bi
208Tl
Counts
100
10
1
0
500
1000
1500
2000
2500
Energy [keV]

Background

Is there anything missing here?

$$\sigma = \frac{N_{\text{detected}}}{N_{\text{inc}} N_{\text{target}} \text{ x efficiency}}$$

$^3He(\alpha,\gamma)^7Be$



Beam

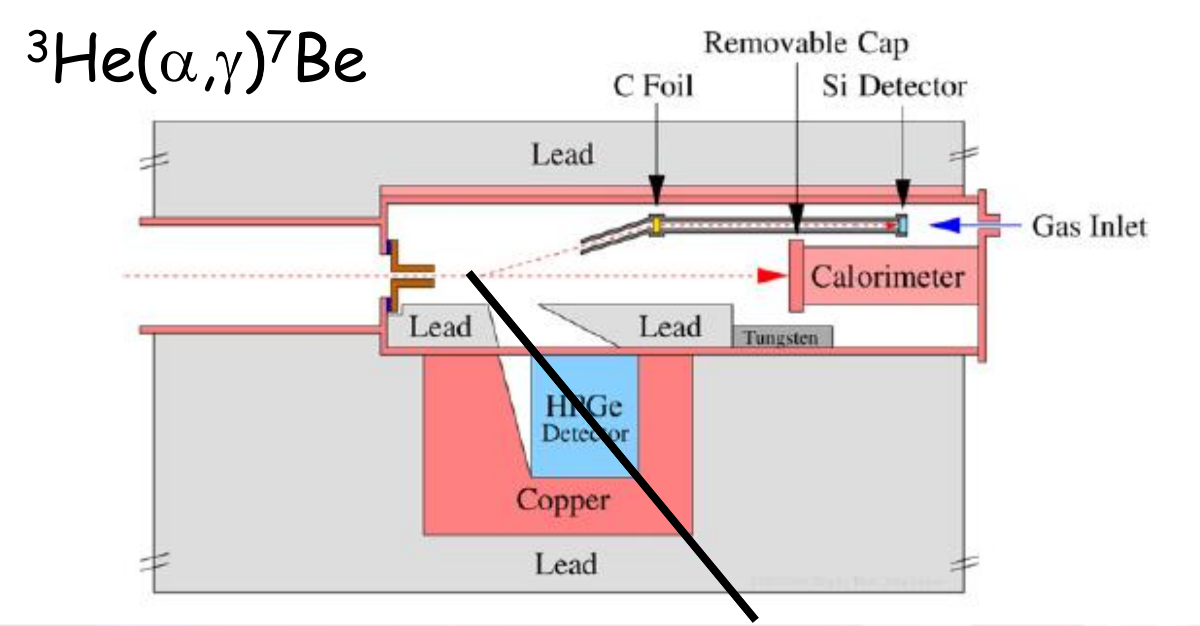
^{4}He

^{3}He

0.7 mbar

What about the angular distribution?

$^{3}He(\alpha,\gamma)^{7}Be$



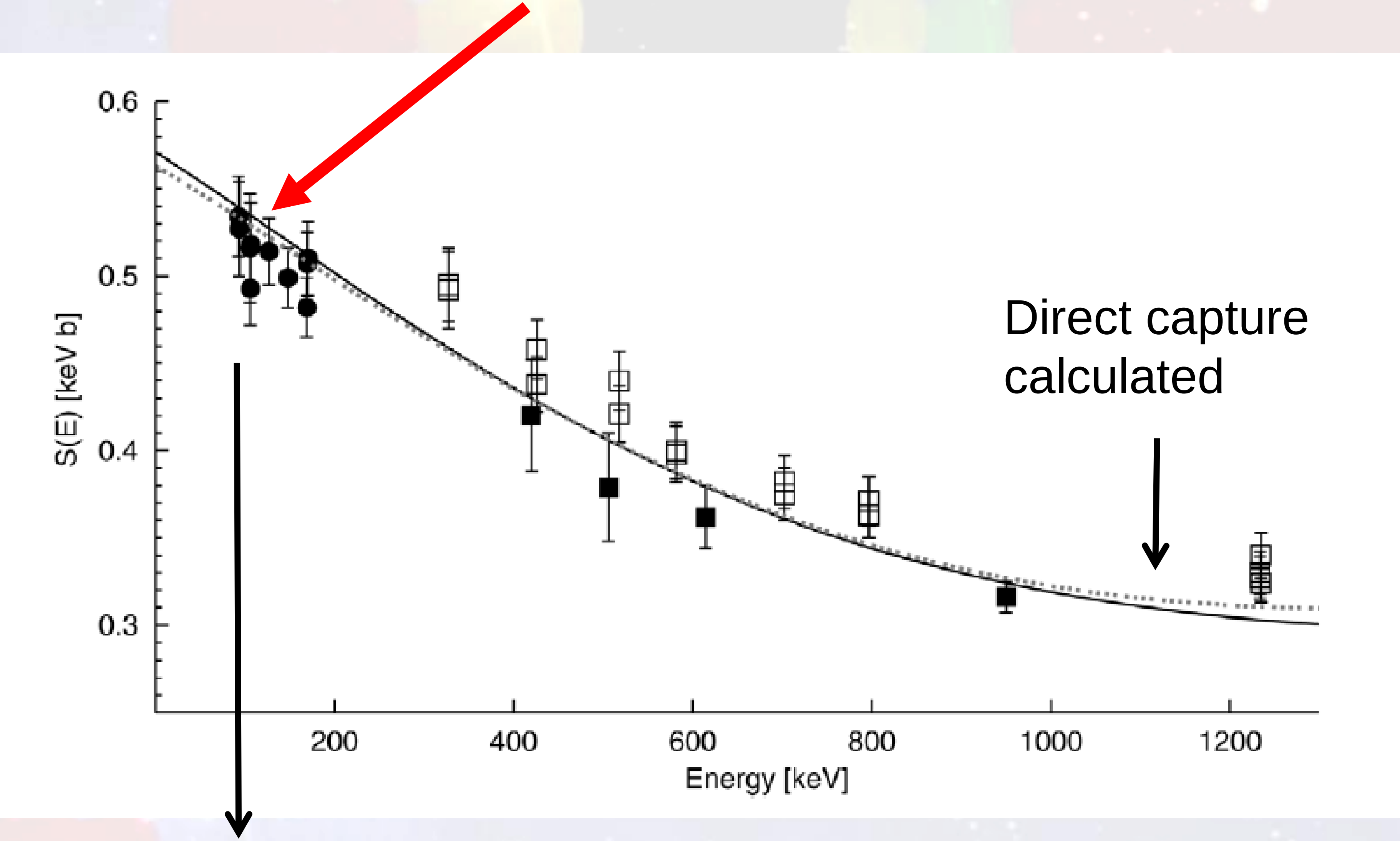
Measured only around θ = 55°

Total cross section **based on theoretical predictions** for the angular distribution + extrapolations

$$W(\theta) = 1 + a_1 P_1(\theta) + a_2 P_2(\theta) + \cdots,$$

where a_1 and a_2 are the coefficients of the Legendre polynomials $P_1(\theta)$ and $P_2(\theta)$.

Resulted in 2.5 % uncertainties…



New results of Luna

Direct capture calculated

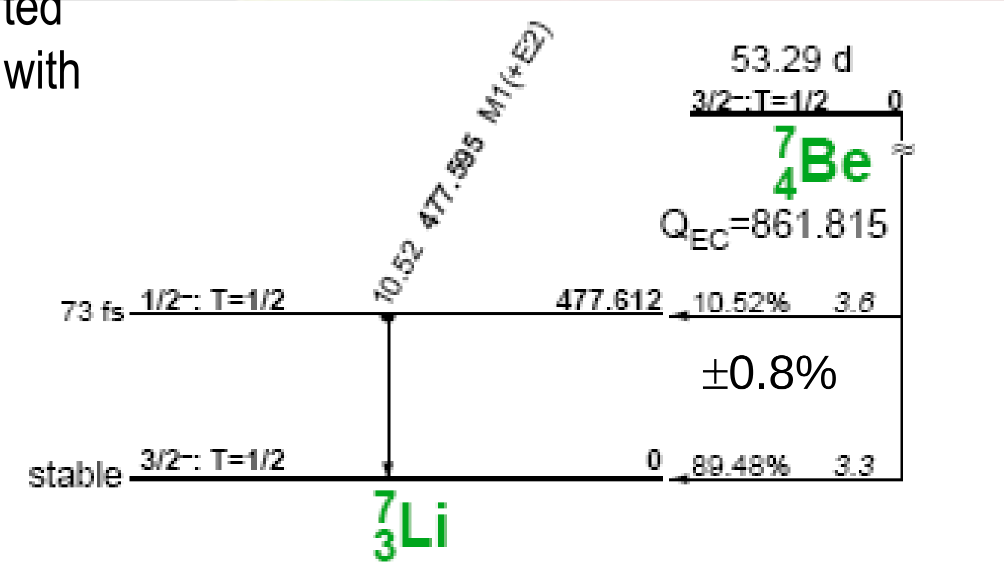
Measured down to 93 keV

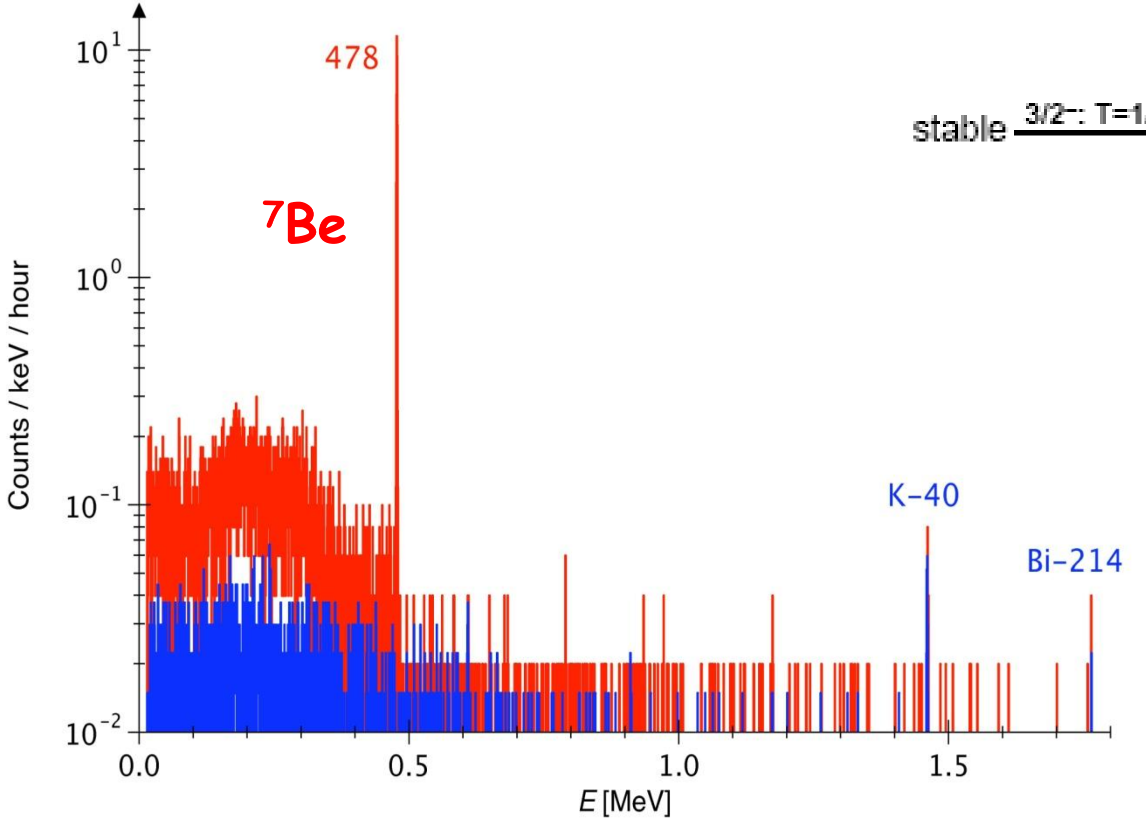
Example 6

Activation measurement

$^{3}He(^{4}He,\gamma)^{7}Be$

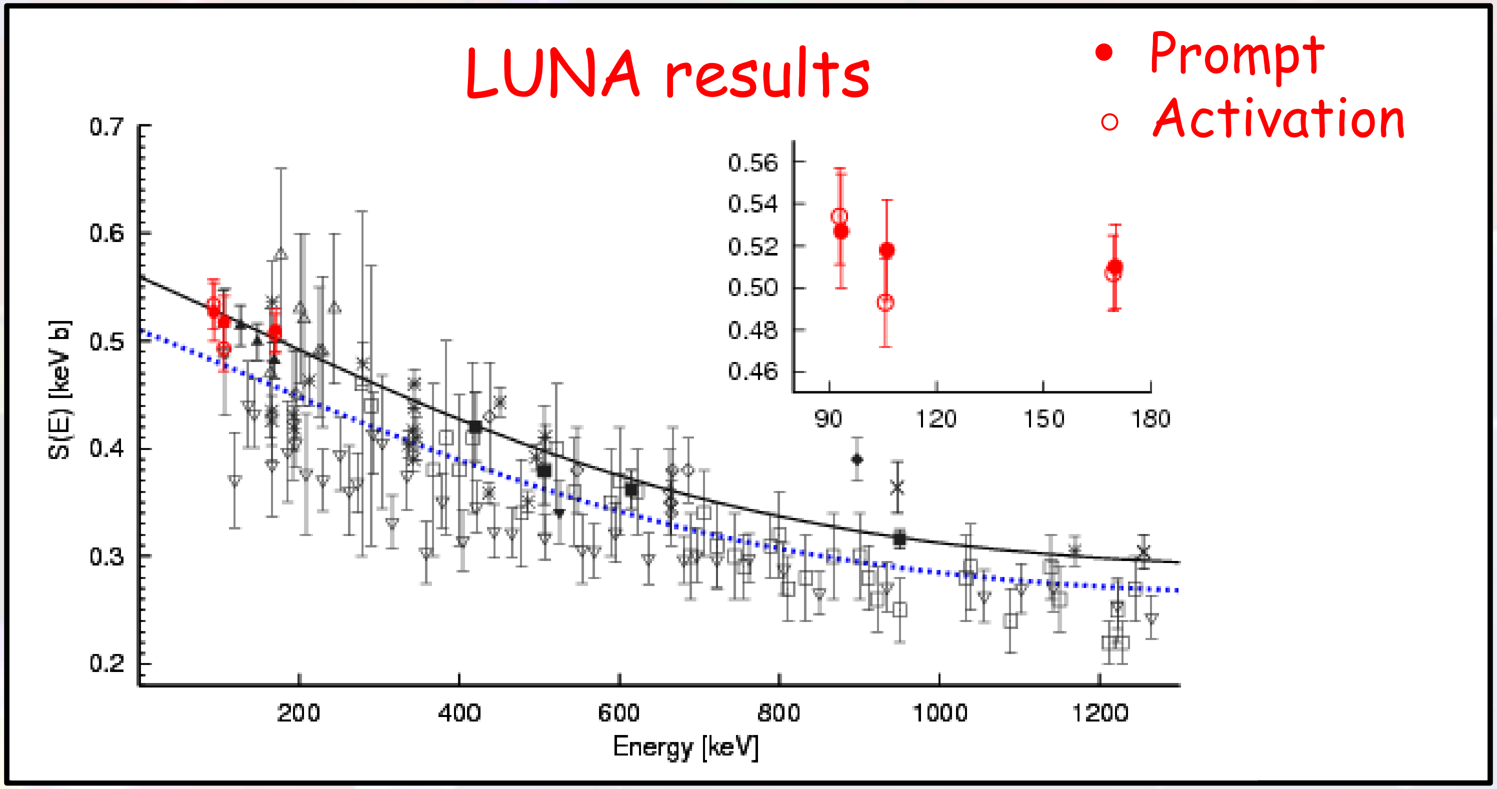
After the irradiation, the catcher was dismounted and counted in close geometry subsequently with two 120% relative efficiency HPGe detectors.





Bemmerer et al., PRL 97(2006)122502

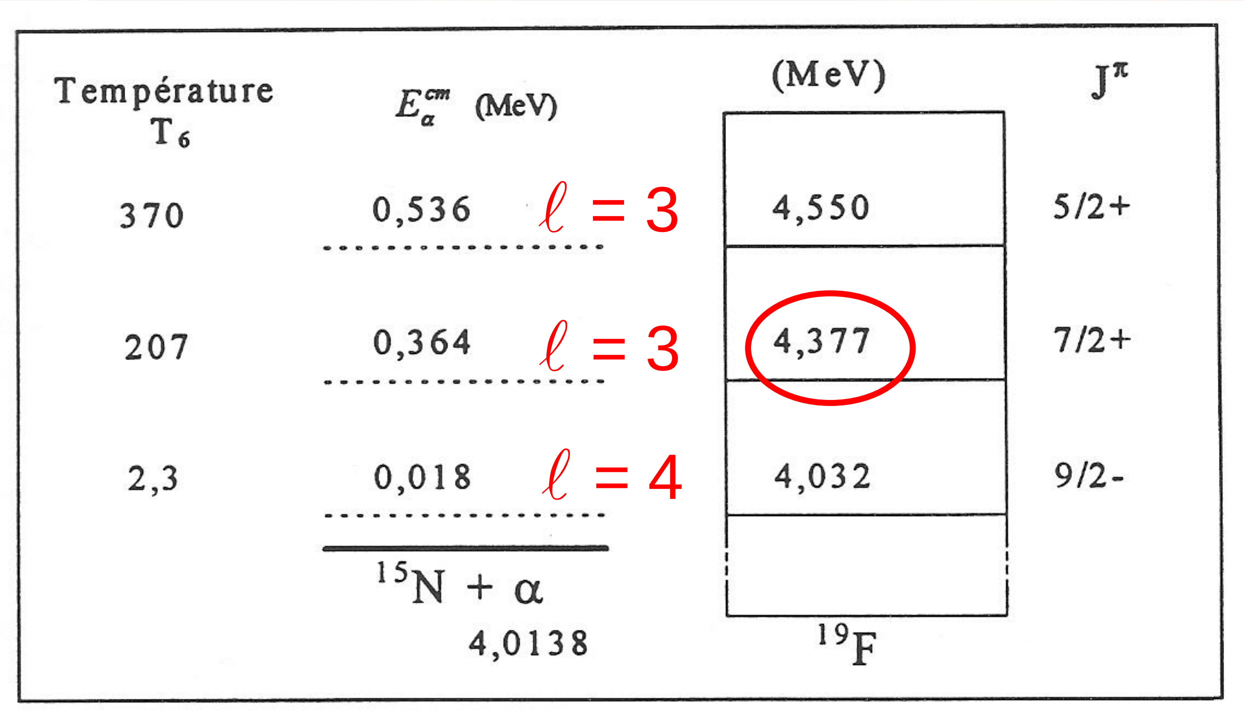
Prompt/ Activation Results



Example 7

Indirect measurement
The case of $^{15}N(\alpha,\gamma)^{19}F$

The main reaction producing ^{19}F in the AGB stars
Rate not well know (quasi) Impossible to measure directly!



Température T_6	E_α^{cm} (MeV)		(MeV)	J^π
370	0,536	$\ell = 3$	4,550	5/2+
207	0,364	$\ell = 3$	4,377	7/2+
2,3	0,018	$\ell = 4$	4,032	9/2-
	$^{15}N + \alpha$ 4,0138		^{19}F	

prediction

$\Gamma_\alpha \sim 9\text{x}10^{-8}$ eV

Impossible to measure directly!?

$$\Gamma_\alpha = \underbrace{S_\alpha} \frac{\hbar^2 s}{\mu} \left|R_L^{DW}(s)\right|^2 P_L(Q,s).$$

Spectroscopic Factor

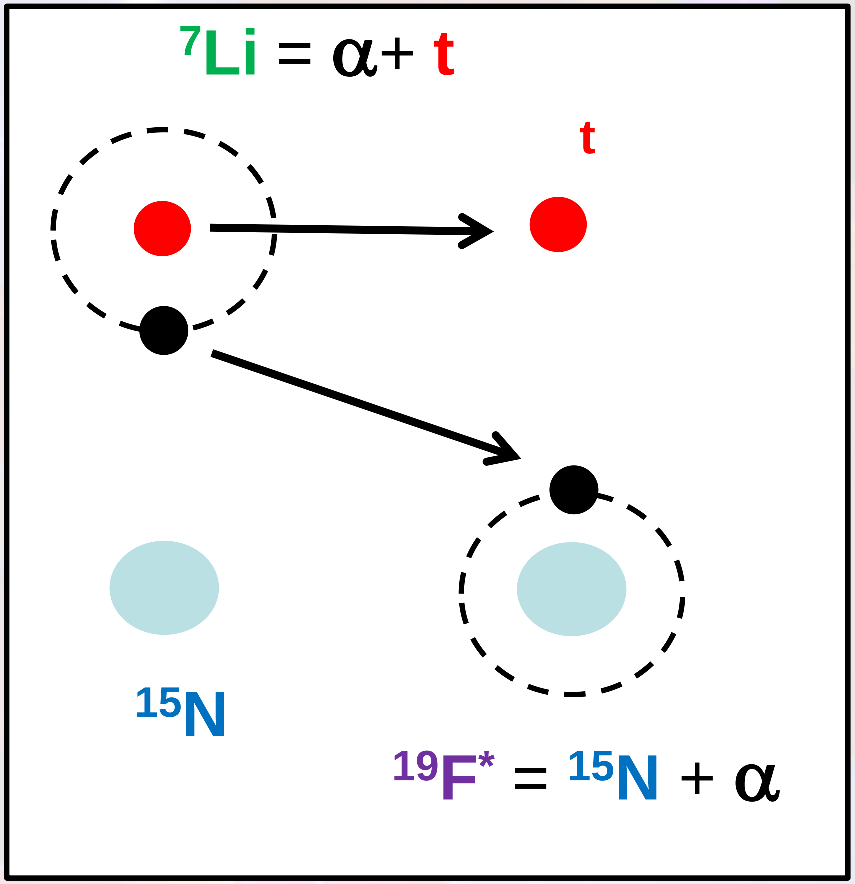
$$S_\alpha = \left| \left\langle {}^{19}F^*(4.377\ \text{MeV}) \middle| {}^{15}N + {}^{4}He \right\rangle \right|^2$$

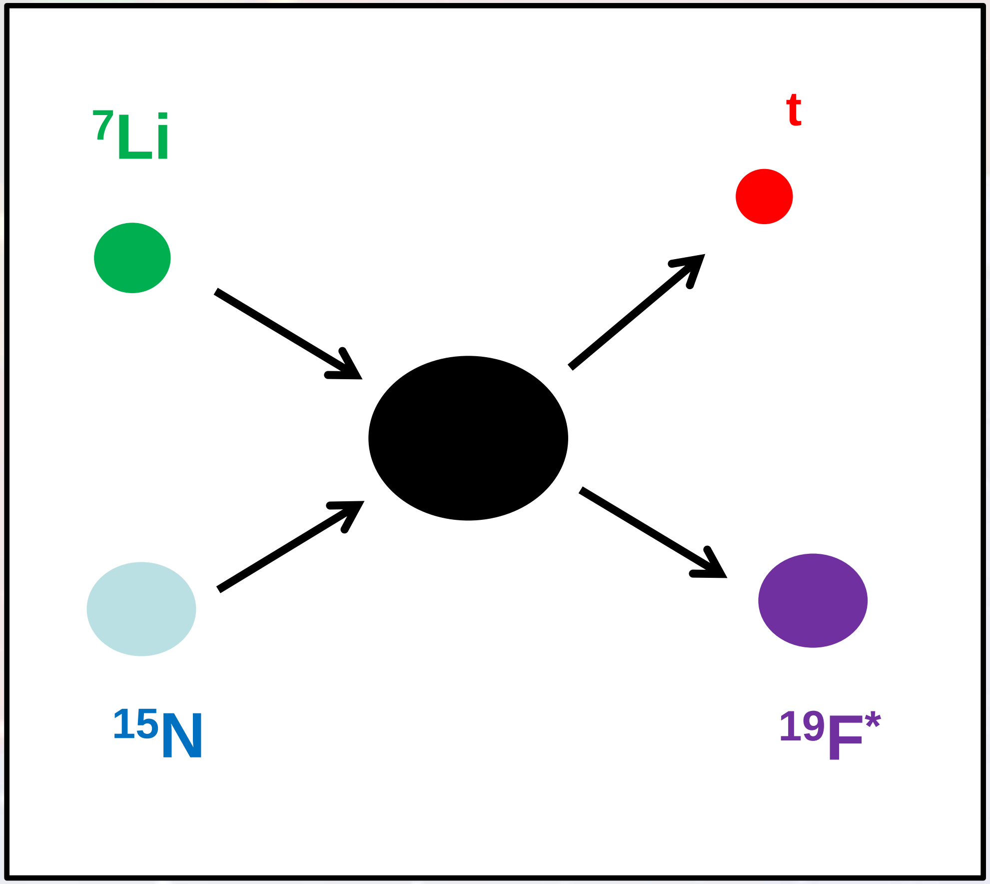
Measurement of $^{15}N(^{7}Li,t)^{19}F$

Two reaction mechanisms

Direct Transfer Reaction

Compound Nucleus





$$\frac{d\sigma}{d\Omega}^{\exp} = SN\left(\frac{d\sigma}{d\Omega}\right)_{DWBA} + C\left(\frac{d\sigma}{d\Omega}\right)_{HSFB}$$

High density of states

Statistical model

Calculate the Compound Nucleus with the Hauser-Feshbach model

$$\sigma_i = \frac{\pi}{k^2}(2\ell+1)\underbrace{T_i}_{\text{Transmission functions}}$$

$$\sigma_{i,f} = \frac{\pi}{k^2}(2\ell+1)\frac{T_i T_f}{\sum_\gamma T_\gamma}.$$

Branching to
final state “f”

$$\sigma_{jk}(E) = \pi \bar{\lambda}_j^2 \frac{1}{(2J_I+1)\left(2J_j+1\right)} \sum_{J\pi}(2J+1)\frac{T_j(E,J^\pi)T_k(E,J^\pi)}{T^\mu_{tot}(E)}$$

Ingredients

- Nuclear Level Density
- Optical potentials
- γ-ray strength functions
-…

Codes

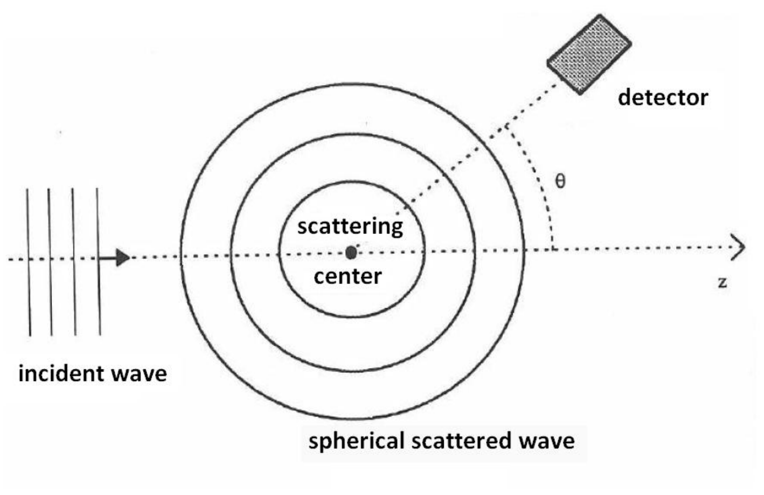
SMOKER, NON-SMOKER, THALYS, MOST,
SMARAGD, HSFB, PACE
http://www.astro.ulb.ac.be/pmwiki/Brusslib/Talys
http://nucastro.org/websmoker.html
Database: KADONIS
…

Calculate the Direct transfer reaction with the DWBA model

Distorted Wave Born Approximation

Reaction A(a,b)B

a = b+x & B = A + x



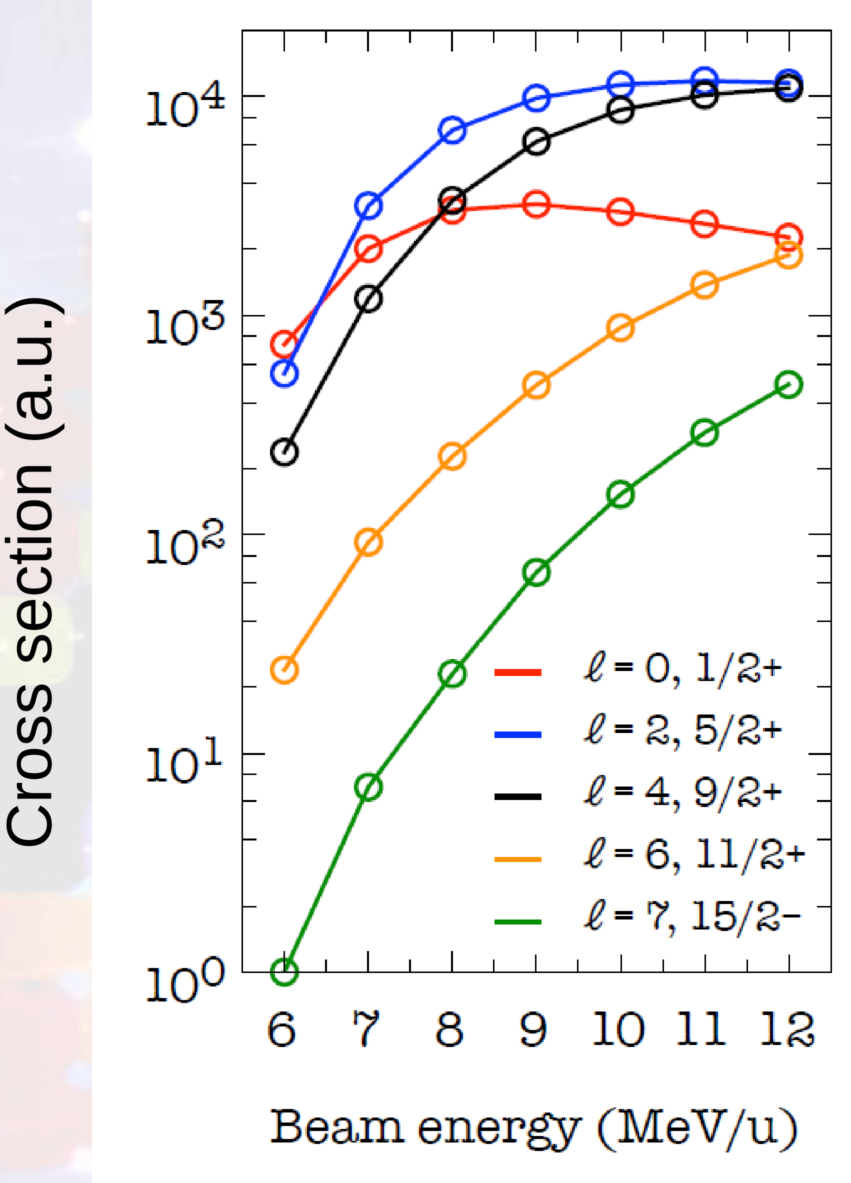
$$\frac{d\sigma}{d\Omega} = \frac{\mu_a \mu_b}{(2\pi\hbar^2)^2}\,\frac{k_b}{k_a}\,\frac{1}{(2J_A+1)(2s_a+1)}\sum_{M_A M_B m_a m_b} |T|^2$$

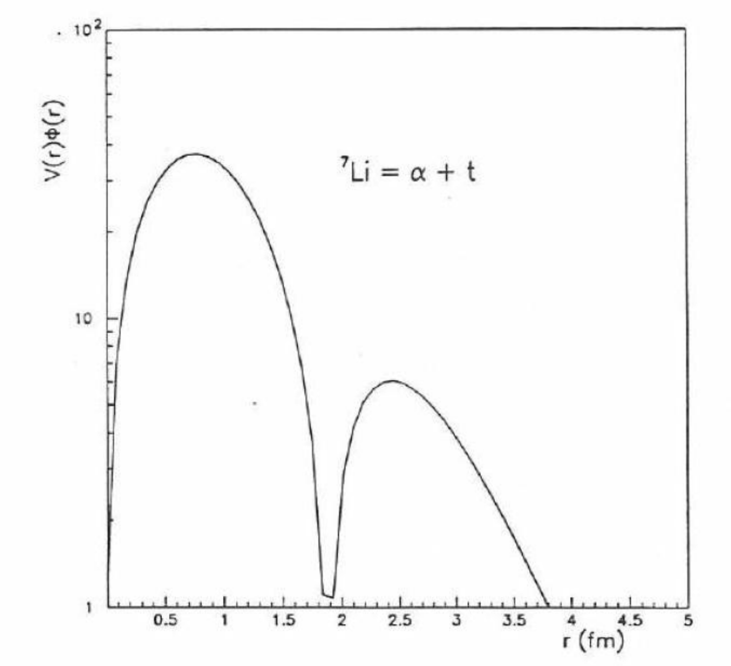
$$T_{DWBA}(\Theta,\Phi) = \int \underbrace{\chi_\beta^{(-)}(\vec{k}_\beta,\vec{r}_\beta)^*}_{\text{B(b,b)B}} \; \underbrace{< \mathrm{B,b}\,|W|\,\mathrm{A,a} >}_{\text{Form factor}} \; \underbrace{\chi_\alpha^{(+)}(\vec{k}_\alpha,\vec{r}_\alpha)}_{\text{Elastic scattering wave function A(a,a)A}} \, d^3\vec{r}_\alpha \, d^3\vec{r}_\beta \,.$$

$$< \mathrm{B,b}\,|W|\,\mathrm{A,a} > \; = \int \underbrace{\Psi_B^* \Psi_b^* \, W \, \Psi_A \Psi_a}_{\text{Internal wave functions}} \, d\xi$$

$$W = V_{bx}.$$

Spin matching

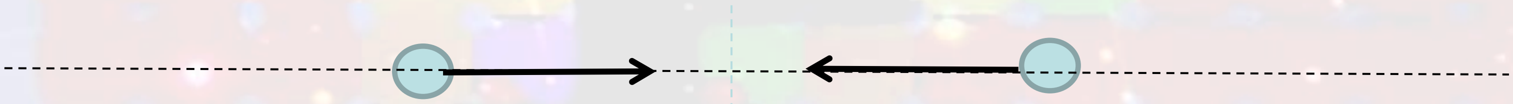


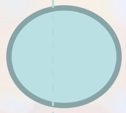


Programs:

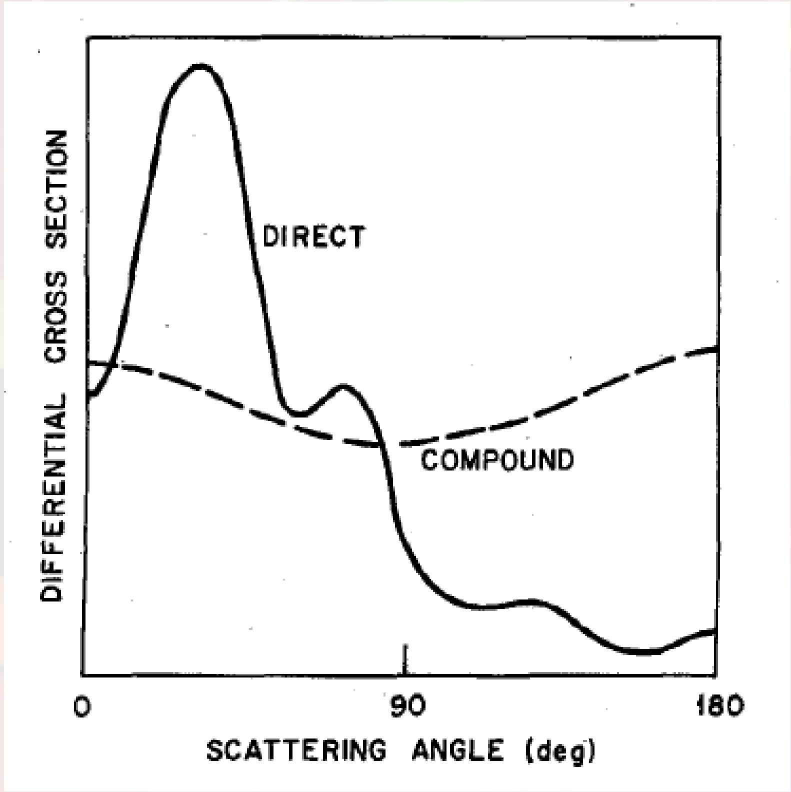
- DWUCK
- PTOLEMY
- FRESCO
  - http://www.fresco.org.uk/
- …

Angular distributions





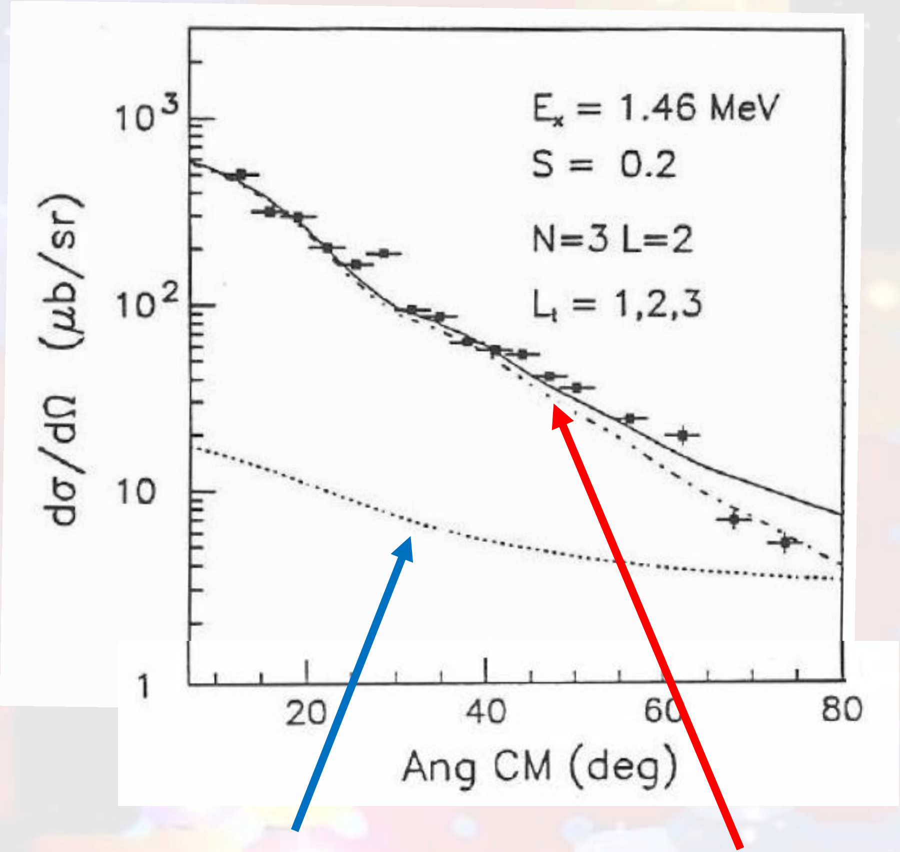
Compound nucleus, no preference for left or right, symmetric around $\theta = 90°$.



Satchler, Introduction to nuclear reactions

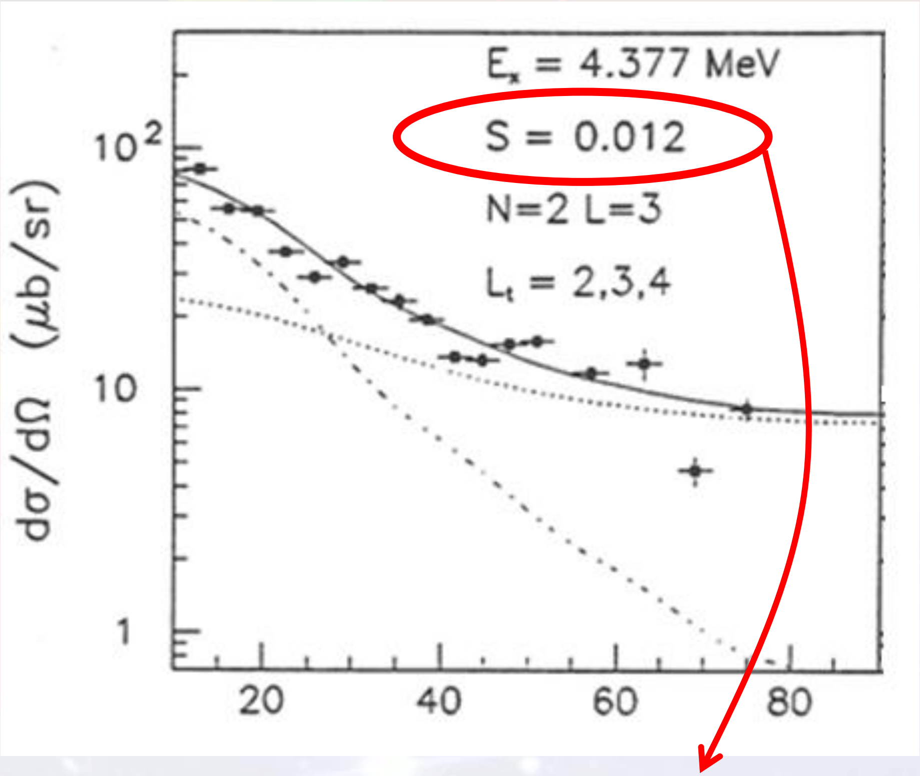
That is not the case for **direct reactions**. Often peaked at 0°.

Results



Hauser-Feshbach

DWBA



$$\Gamma_\alpha = (1.5^{+1.5}_{-0.8}) \text{ x } 10^{-9} \text{ eV}$$

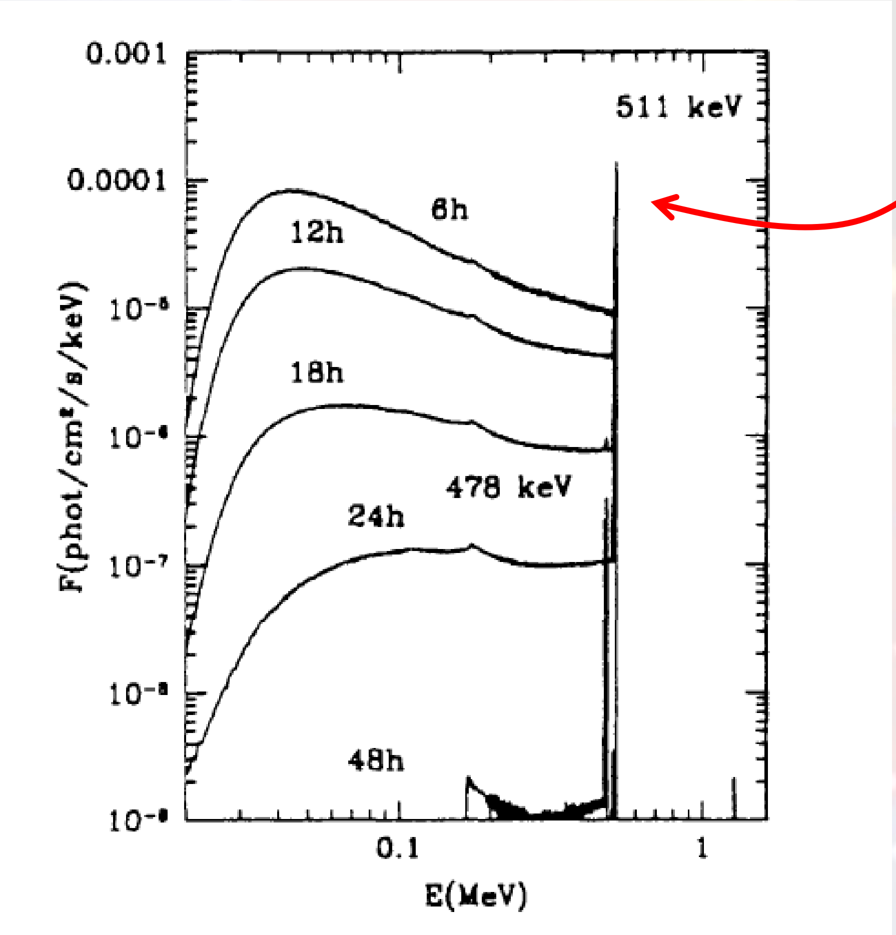
(Orsay - 28 MeV)

Ref. '**Determination of alpha widths in ^{19}F relevant to fluorine nucleosynthesis**'
F. de Oliveira, A. Coc,et al.
Nuclear Physics A 597 (1996) 231-252

Example 8

Novae explosions

Predicted Gamma-ray flux



^{18}F *β+ decay*

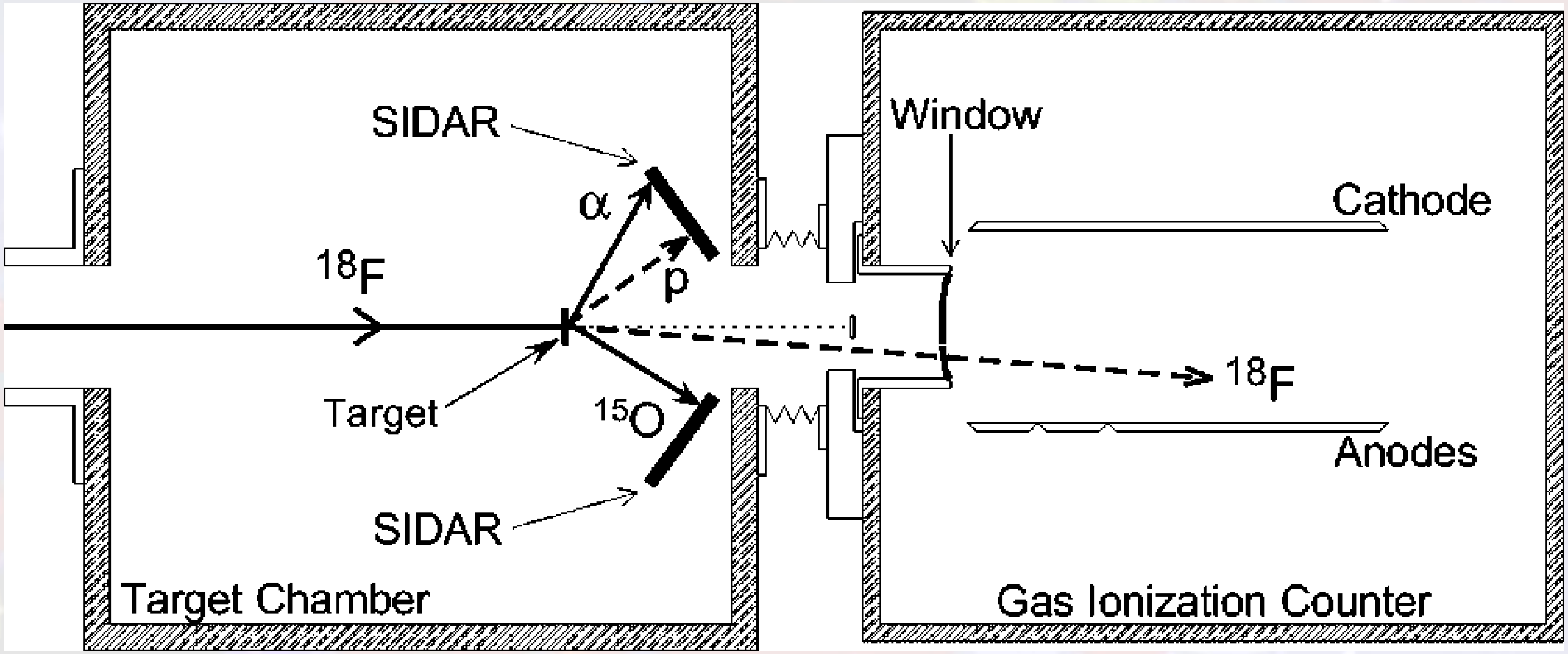
- Large Uncertainties remain, especially in **^{18}F(p,α)^{15}O**

- Reaction rate is determined by resonant contributions from states in the compound nucleus **^{19}Ne**

M. Hernanz, J. Jose, A. Coc, J. Gomez-Gomar, and J. Isern, Astrophys. J. 526, L97 (1999).

A. Coc, M. Hernanz, J. Jose, and J.-P. Thibaud, Astron. Astrophys. 357, 561 (2000).

ORNL - Holifield Radioactive Ion Beam Facility

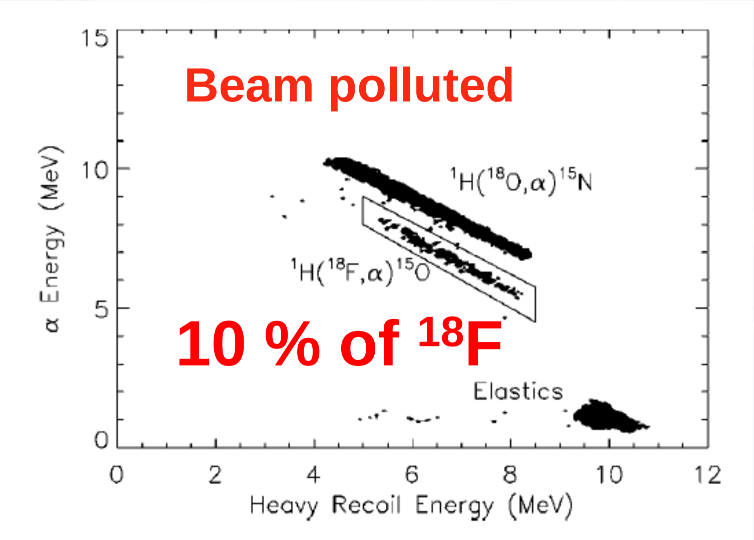


Hydrogen rich target

$H(^{18}F,p)^{18}F$

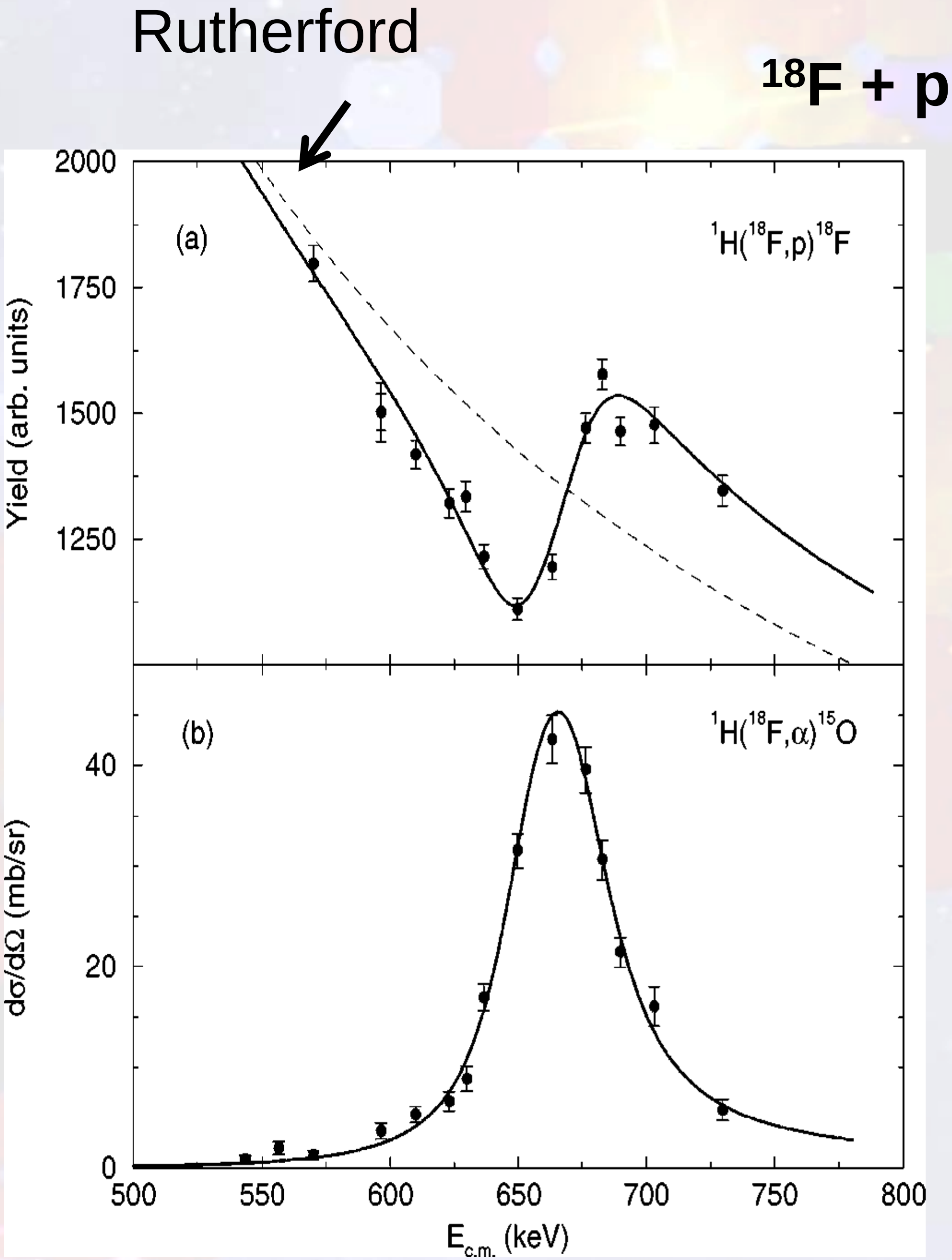
$H(^{18}F,\alpha)^{15}O$

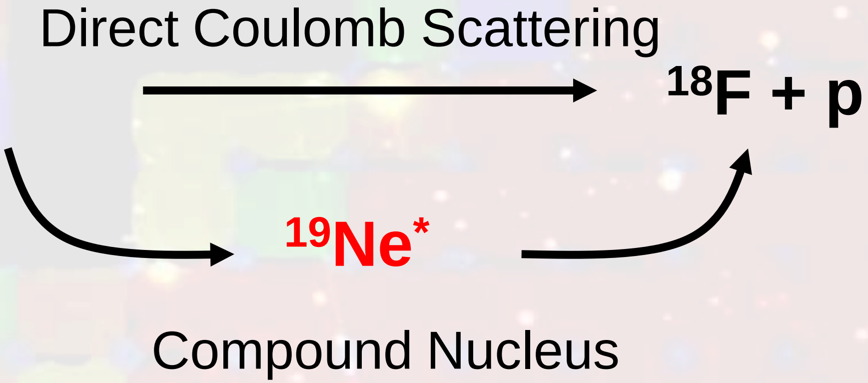
Using a thin target and changing the beam energy by small steps


Beam polluted

10 % of ^{18}F

Bardayan et al, Phys. Rev C, V63, 065802 (2001)




^{18}F + p

Direct Coulomb Scattering

^{18}F + p

^{19}Ne*

Compound Nucleus

Position $\Rightarrow E_x$

Width of the peak $\Rightarrow \Gamma$

Analysis of the spectra through the R-Matrix formalism

R-matrix formalism

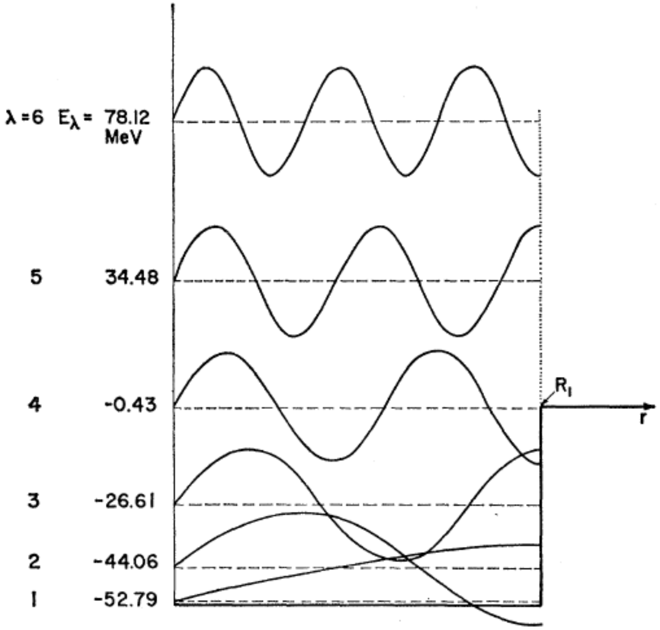


FIG. 2. The first six standing waves of the square well, constructed with a boundary condition number ($b = 0$) appropriate to low-energy scattering.

Read
[Vogt, Erich Rev. Mod. Phys. 34 p72]
Charity Eur. Phys. J. Plus (2016) 131:63

Because the X_λ form a complete orthonormal set of functions, the actual wave function ϕ may be expanded in terms of them

$$\phi = \sum_\lambda C_\lambda X_\lambda$$

The scattering of s-wave neutrons by a square well :

$$\sigma = \frac{\pi}{k^2}\left|\underbrace{2\sin kR_1 e^{ikR_1}} - \frac{\Gamma_\lambda}{(E_\lambda - E + \Delta_\lambda) - \frac{1}{2}i\Gamma_\lambda}\right|^2$$

Scattering due to a hard sphere of radius R_1

where

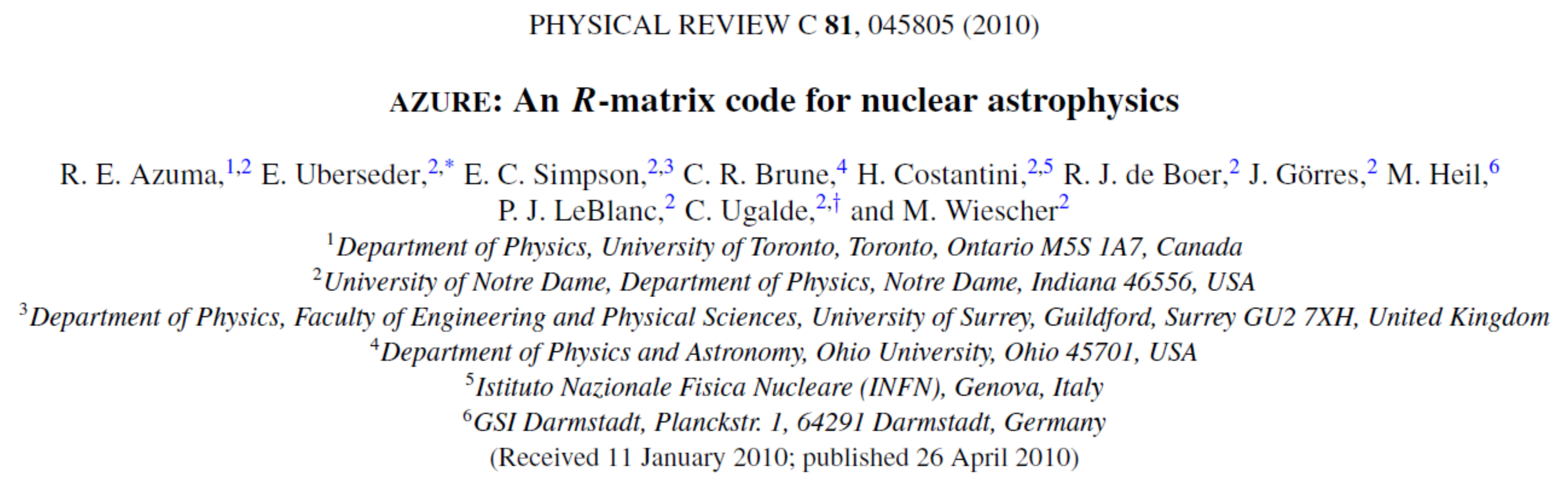
$$\Gamma_\lambda \equiv 2kR_1\gamma_\lambda^2$$

$$\Delta \equiv b\gamma_\lambda^2$$

$$\gamma_\lambda^2 \equiv (\hbar^2/2mR_1)|X_\lambda(R_1)|^2$$ = reduced width

The multichannel R-matrix code AZURE

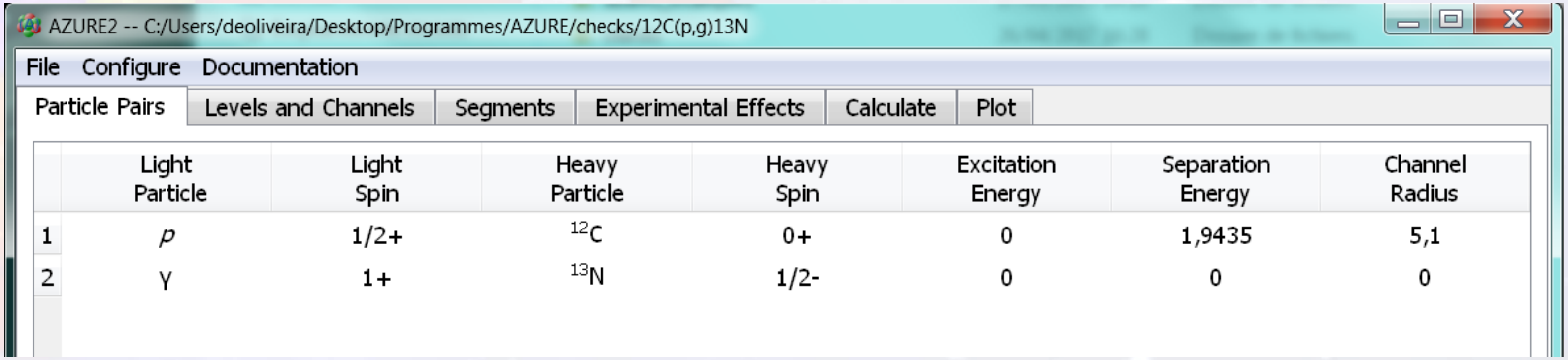
Only for Relatively low density of states



PHYSICAL REVIEW C **81**, 045805 (2010)

AZURE: An *R*-matrix code for nuclear astrophysics

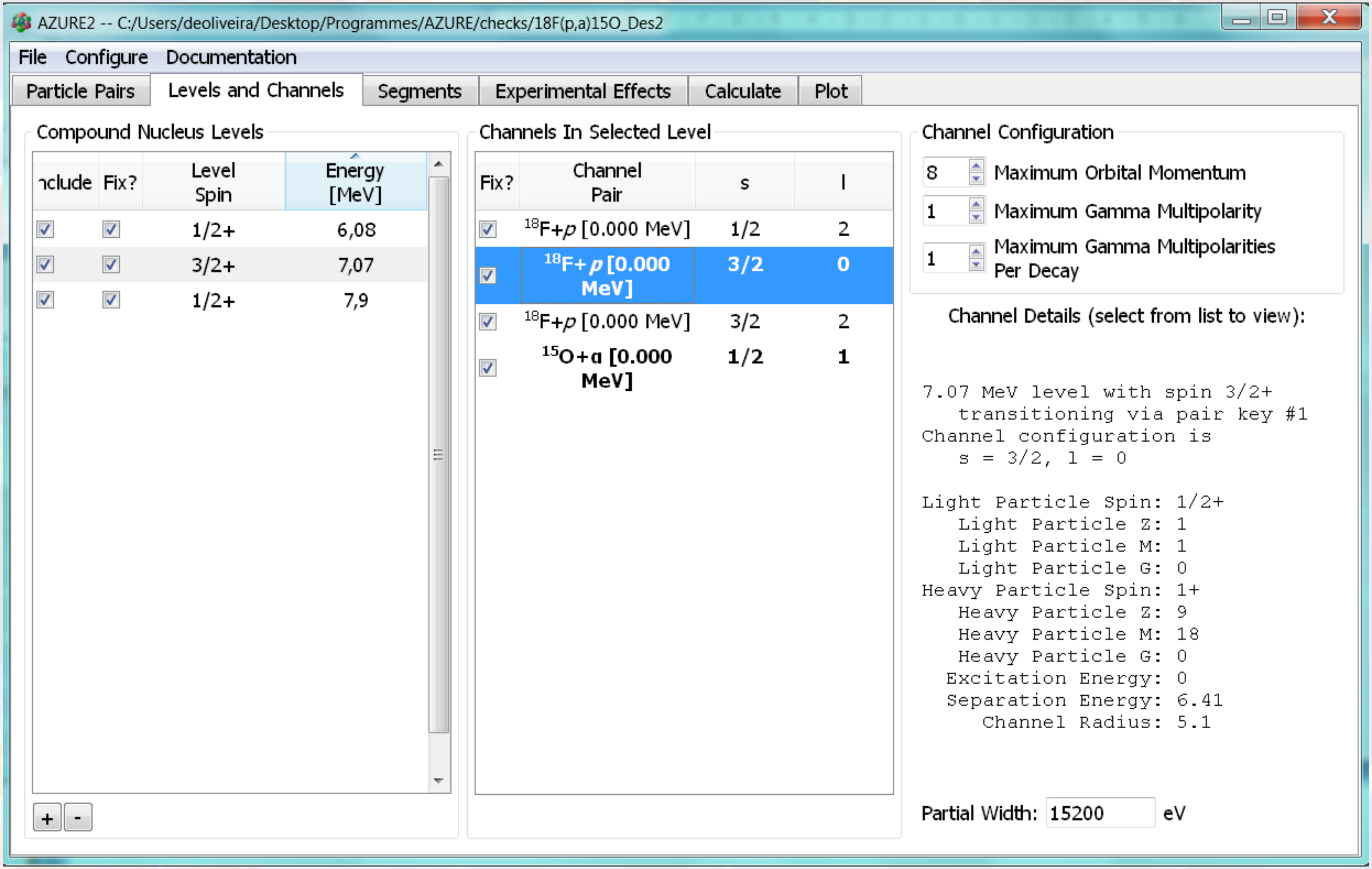
R. E. Azuma,[1,2] E. Uberseder,[2,*] E. C. Simpson,[2,3] C. R. Brune,[4] H. Costantini,[2,5] R. J. de Boer,[2] J. Görres,[2] M. Heil,[6]
P. J. LeBlanc,[2] C. Ugalde,[2,†] and M. Wiescher[2]
[1]*Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada*
[2]*University of Notre Dame, Department of Physics, Notre Dame, Indiana 46556, USA*
[3]*Department of Physics, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford, Surrey GU2 7XH, United Kingdom*
[4]*Department of Physics and Astronomy, Ohio University, Ohio 45701, USA*
[5]*Istituto Nazionale Fisica Nucleare (INFN), Genova, Italy*
[6]*GSI Darmstadt, Planckstr. 1, 64291 Darmstadt, Germany*
(Received 11 January 2010; published 26 April 2010)



AZURE2 -- C:/Users/deoliveira/Desktop/Programmes/AZURE/checks/12C(p,g)13N

	Light Particle	Light Spin	Heavy Particle	Heavy Spin	Excitation Energy	Separation Energy	Channel Radius
1	p	1/2+	^{12}C	0+	0	1,9435	5,1
2	γ	1+	^{13}N	1/2-	0	0	0

https://azure.nd.edu/downloads.php



Compound Nucleus Levels

nclude	Fix?	Level Spin	Energy [MeV]
☑	☑	1/2+	6,08
☑	☑	3/2+	7,07
☑	☑	1/2+	7,9

Channels In Selected Level

Fix?	Channel Pair	s	l
☑	^{18}F+p [0.000 MeV]	1/2	2
☑	**^{18}F+p [0.000 MeV]**	**3/2**	**0**
☑	^{18}F+p [0.000 MeV]	3/2	2
☑	**^{15}O+α [0.000 MeV]**	**1/2**	**1**

Channel Configuration

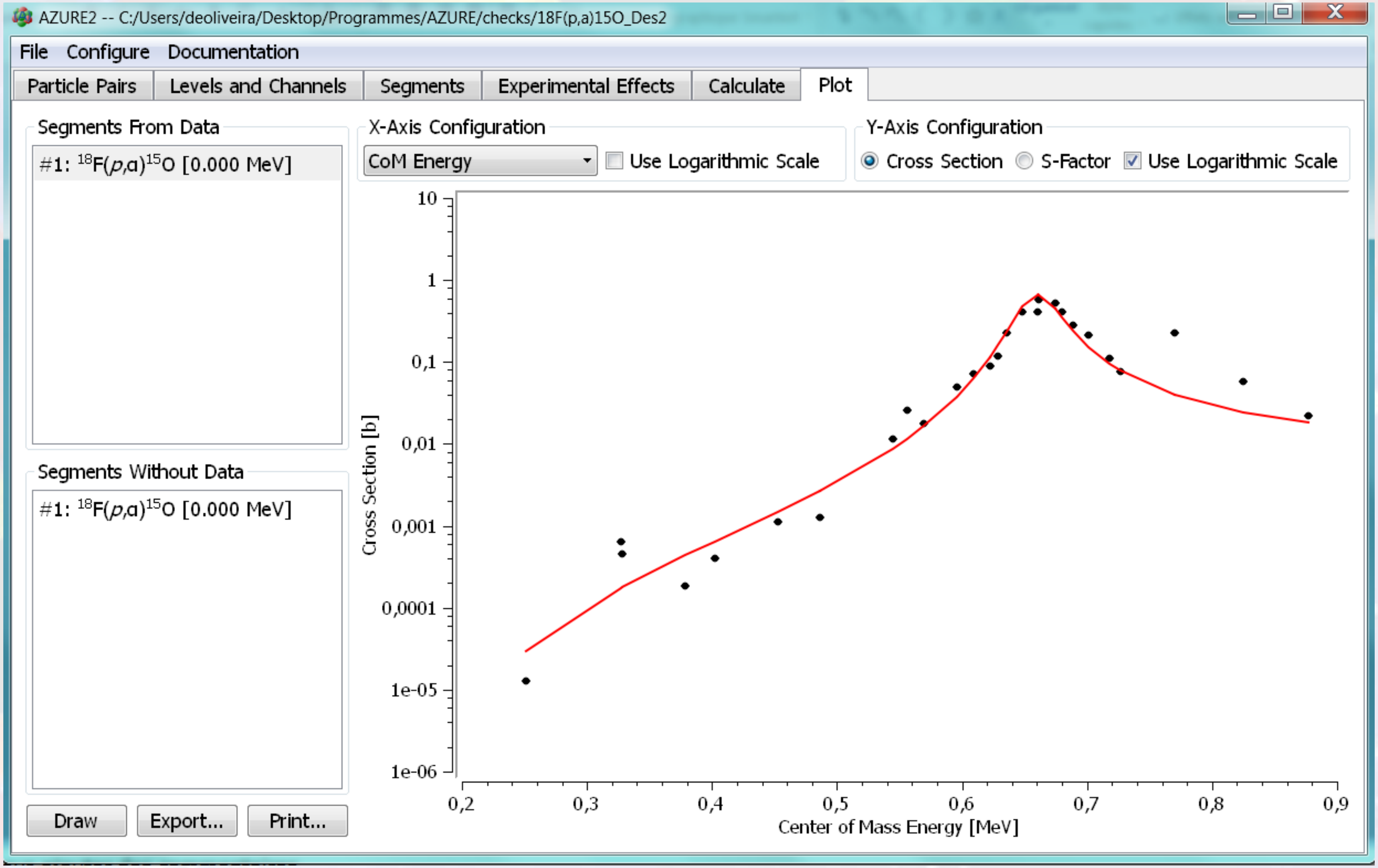
8 Maximum Orbital Momentum
1 Maximum Gamma Multipolarity
1 Maximum Gamma Multipolarities Per Decay

Channel Details (select from list to view):

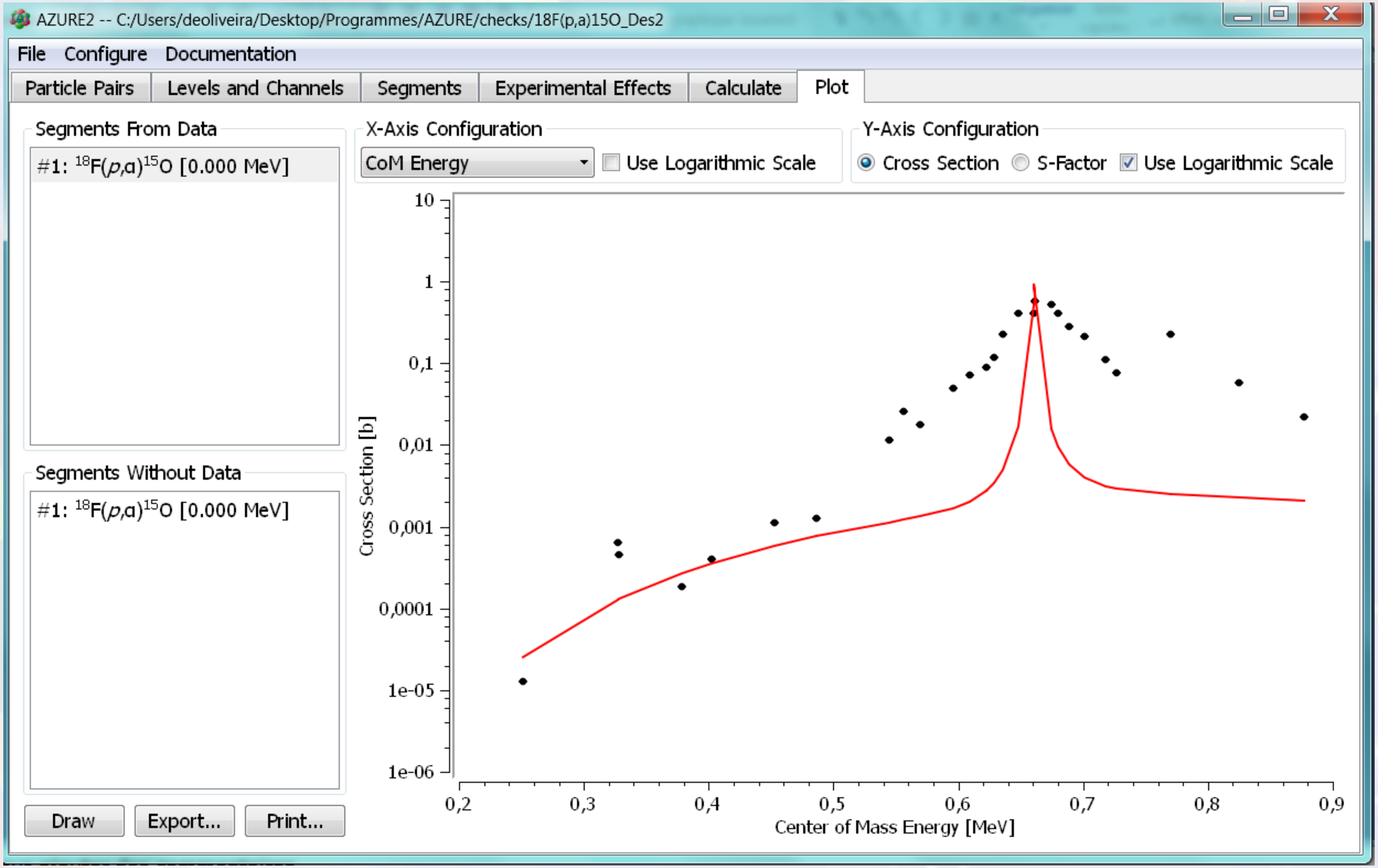
```
7.07 MeV level with spin 3/2+
   transitioning via pair key #1
Channel configuration is
   s = 3/2, l = 0

Light Particle Spin: 1/2+
   Light Particle Z: 1
   Light Particle M: 1
   Light Particle G: 0
Heavy Particle Spin: 1+
   Heavy Particle Z: 9
   Heavy Particle M: 18
   Heavy Particle G: 0
  Excitation Energy: 0
  Separation Energy: 6.41
     Channel Radius: 5.1
```

Partial Width: 15200 eV

J=3/2+


AZURE2 -- C:/Users/deoliveira/Desktop/Programmes/AZURE/checks/18F(p,a)15O_Des2
File
Configure
Documentation
Particle Pairs
Levels and Channels
Segments
Experimental Effects
Calculate
Plot
Segments From Data
#1: 18F(p,α)15O [0.000 MeV]
Segments Without Data
#1: 18F(p,α)15O [0.000 MeV]
Draw
Export...
Print...
X-Axis Configuration
CoM Energy
☐ Use Logarithmic Scale
Y-Axis Configuration
● Cross Section
○ S-Factor
☑ Use Logarithmic Scale
10
1
0,1
0,01
0,001
0,0001
1e-05
1e-06
Cross Section [b]
0,2
0,3
0,4
0,5
0,6
0,7
0,8
0,9
Center of Mass Energy [MeV]

J=5/2+



AZURE2 -- C:/Users/deoliveira/Desktop/Programmes/AZURE/checks/18F(p,a)15O_Des2

Segments From Data

#1: ^{18}F(*p*,α)^{15}O [0.000 MeV]

Segments Without Data

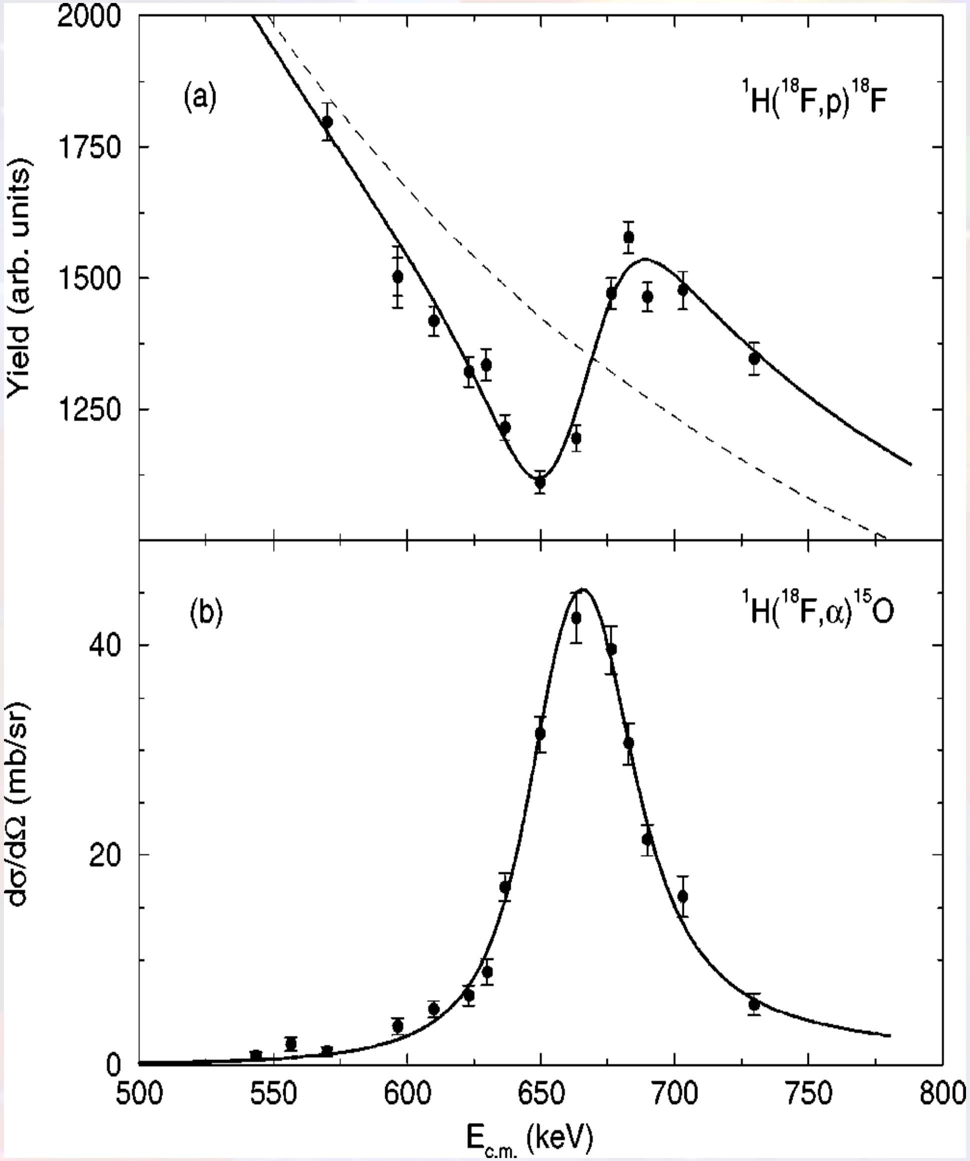
#1: ^{18}F(*p*,α)^{15}O [0.000 MeV]

X-Axis Configuration

CoM Energy ☐ Use Logarithmic Scale

Y-Axis Configuration

● Cross Section ○ S-Factor ☑ Use Logarithmic Scale



E_x = 7076 ± 2 keV

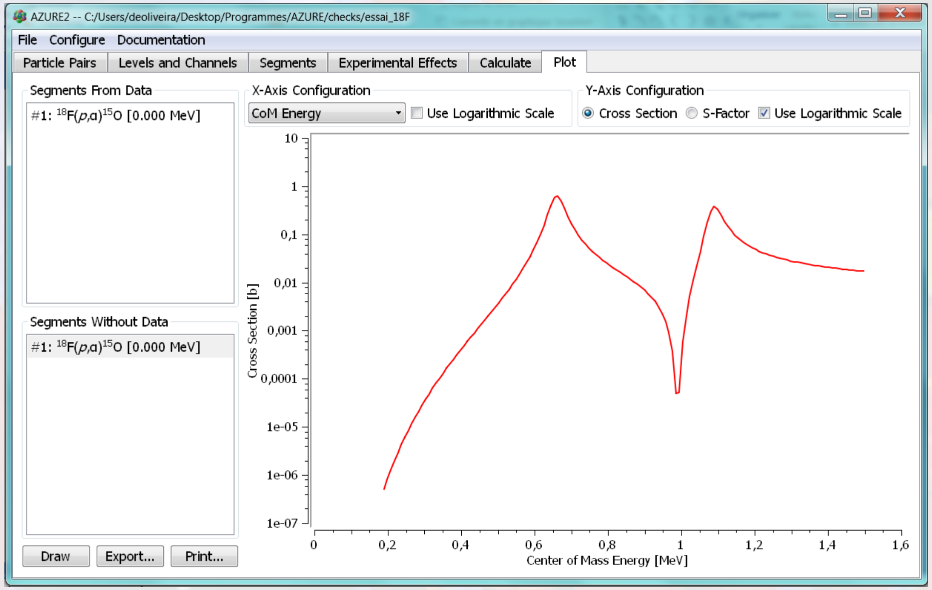
ℓ = 0   1/2+ or 3/2+

Γ= 39.0 ± 1.6 keV

Γ_p/Γ= 0.39 ± 0.02

$$J^{\pi} = \frac{3}{2}^{+}$$

Interferences between two states



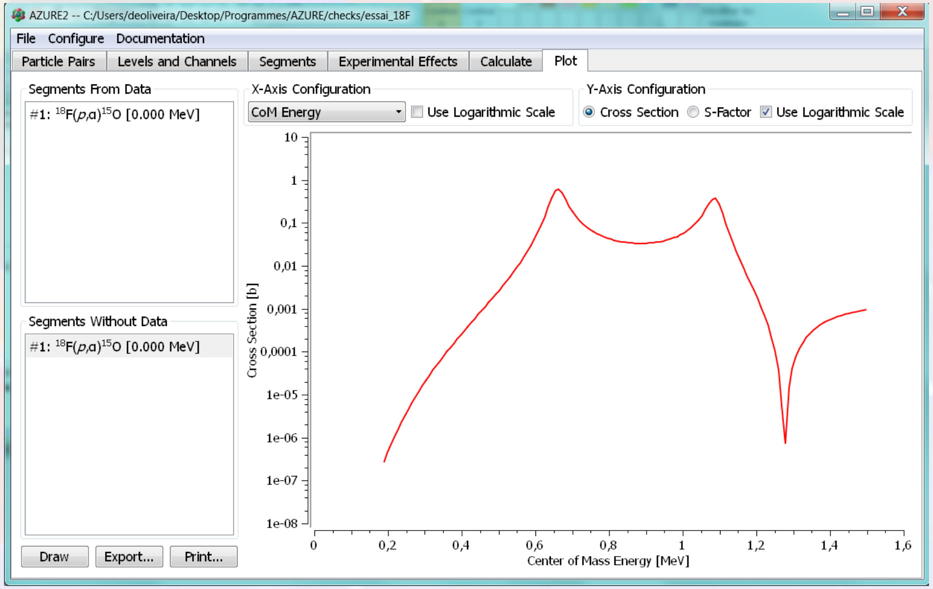
AZURE2 -- C:/Users/deoliveira/Desktop/Programmes/AZURE/checks/essai_18F

Segments From Data: #1: ^{18}F(p,α)^{15}O [0.000 MeV]

Segments Without Data: #1: ^{18}F(p,α)^{15}O [0.000 MeV]

X-Axis Configuration: CoM Energy ☐ Use Logarithmic Scale

Y-Axis Configuration: ● Cross Section ○ S-Factor ☑ Use Logarithmic Scale



AZURE2 -- C:/Users/deoliveira/Desktop/Programmes/AZURE/checks/essai_18F

Segments From Data: #1: ^{18}F(p,α)^{15}O [0.000 MeV]

Segments Without Data: #1: ^{18}F(p,α)^{15}O [0.000 MeV]

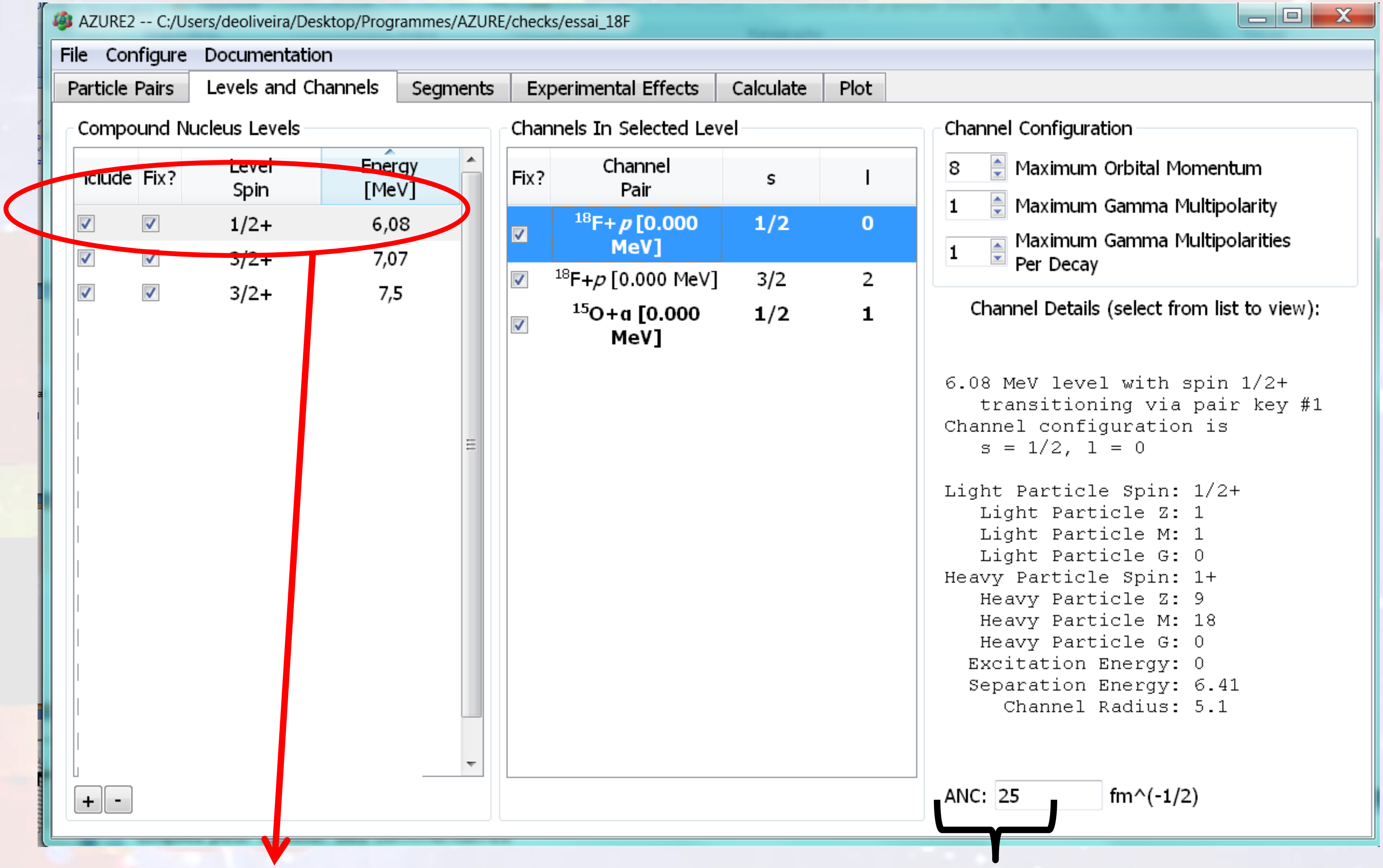
X-Axis Configuration: CoM Energy ☐ Use Logarithmic Scale

Y-Axis Configuration: ● Cross Section ○ S-Factor ☑ Use Logarithmic Scale

Two hypothetical 3/2+ states in ^{19}Ne interfering

The sign of the width matters

Subthreshold resonance



Compound Nucleus Levels

nclude	Fix?	Level Spin	Energy [MeV]
☑	☑	1/2+	6,08
☑	☑	3/2+	7,07
☑	☑	3/2+	7,5

Channels In Selected Level

Fix?	Channel Pair	s	l
☑	**^{18}F+*p* [0.000 MeV]**	**1/2**	**0**
☑	^{18}F+*p* [0.000 MeV]	3/2	2
☑	**^{15}O+α [0.000 MeV]**	**1/2**	**1**

Channel Configuration

8 Maximum Orbital Momentum
1 Maximum Gamma Multipolarity
1 Maximum Gamma Multipolarities Per Decay

Channel Details (select from list to view):

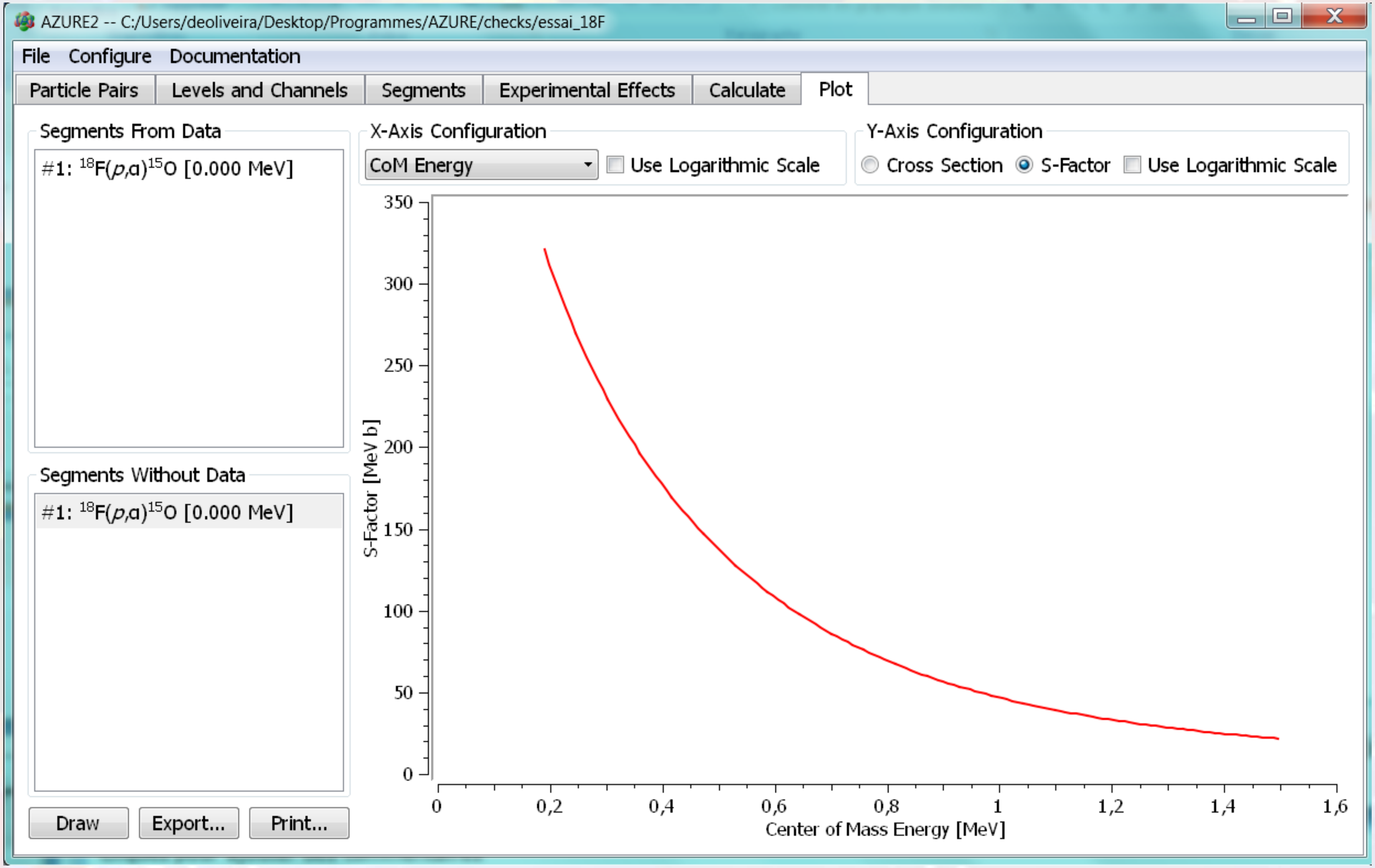
```
6.08 MeV level with spin 1/2+
   transitioning via pair key #1
Channel configuration is
   s = 1/2, l = 0

Light Particle Spin: 1/2+
   Light Particle Z: 1
   Light Particle M: 1
   Light Particle G: 0
Heavy Particle Spin: 1+
   Heavy Particle Z: 9
   Heavy Particle M: 18
   Heavy Particle G: 0
  Excitation Energy: 0
  Separation Energy: 6.41
     Channel Radius: 5.1
```

ANC: 25 fm^(-1/2)

Sp = 6.410 MeV
Subthreshold state

Asymptotic normalization coefficient

Subthreshold resonance



AZURE2 -- C:/Users/deoliveira/Desktop/Programmes/AZURE/checks/essai_18F

Segments From Data

#1: ^{18}F(p,α)^{15}O [0.000 MeV]

Segments Without Data

#1: ^{18}F(p,α)^{15}O [0.000 MeV]

X-Axis Configuration

CoM Energy ☐ Use Logarithmic Scale

Y-Axis Configuration

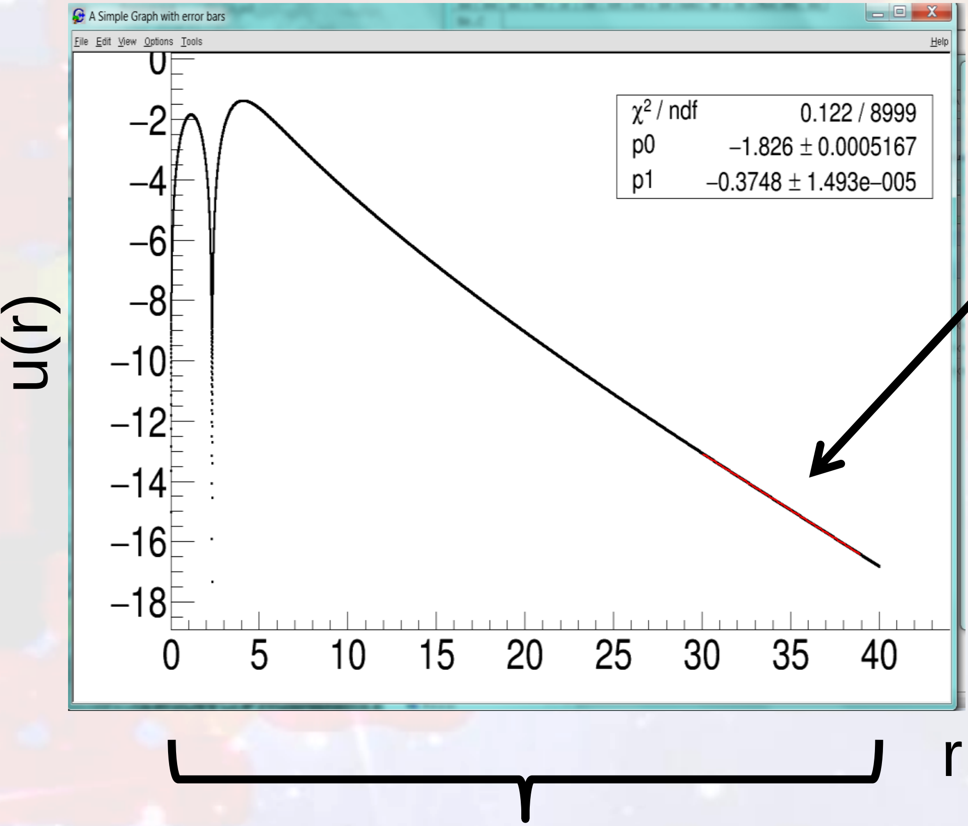
○ Cross Section ● S-Factor ☐ Use Logarithmic Scale

Subthreshold resonance

$ANC^{exp} = S \times ANC^{single\ particle}$

S spectroscopic factor

Wave function can be calculated with code dwu or RADCAP



χ^2 / ndf	0.122 / 8999
p0	−1.826 ± 0.0005167
p1	−0.3748 ± 1.493e−005

$$u_\ell(r) = ANC^{s.p.} \text{ x } W_{-\eta,\ell+1/2}(-2k_p r$$

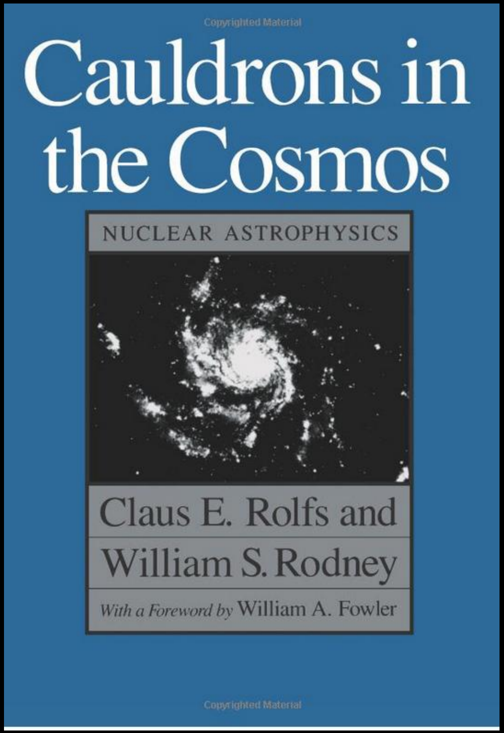
Fitted with the Whittaker function for r→∞

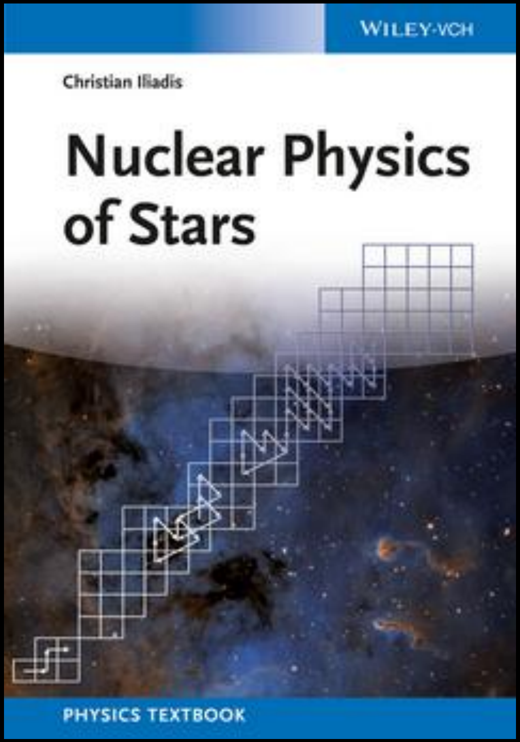
Single-particle wave function $^{19}Ne = {}^{18}F + p$ 2s1/2

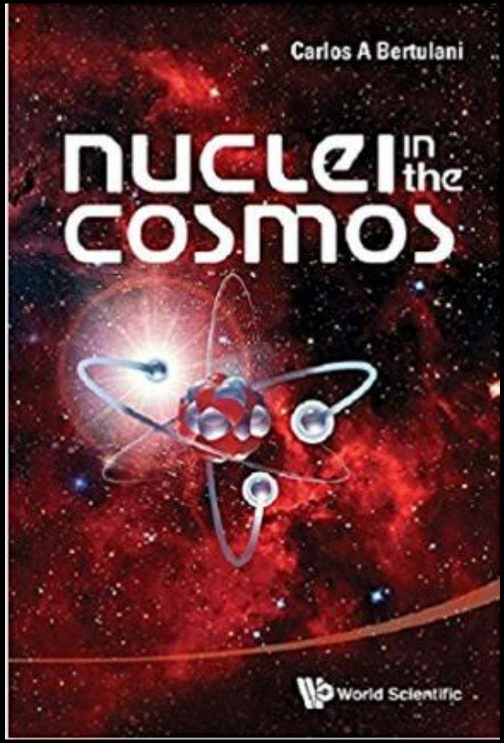
Conclusion

This was just a brief introduction!
There are many more aspects to discover

http://cococubed.asu.edu/index.html
https://nucastro.org/Welcome.html
http://mesa.sourceforge.net/index.html







The end

Thank you