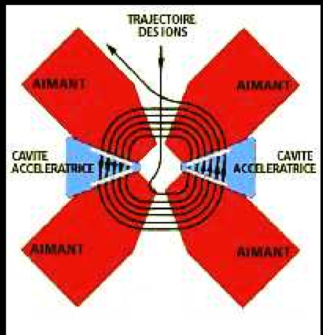
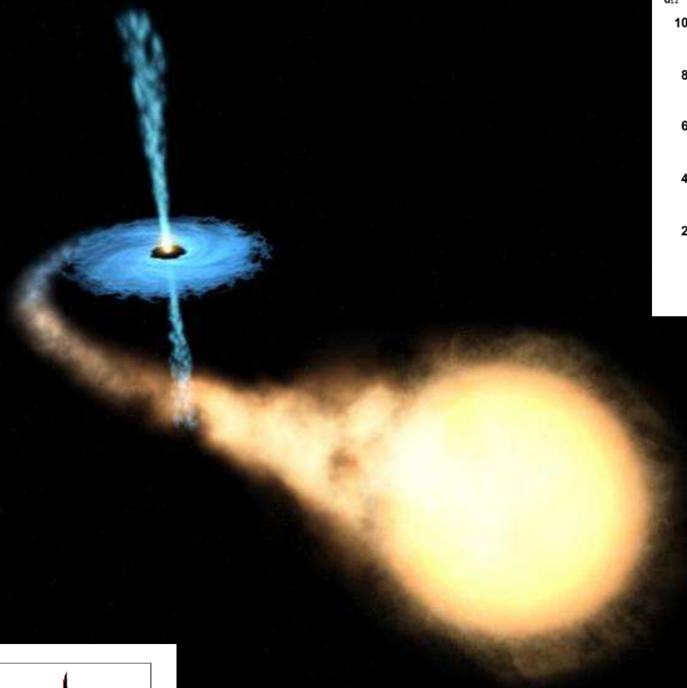
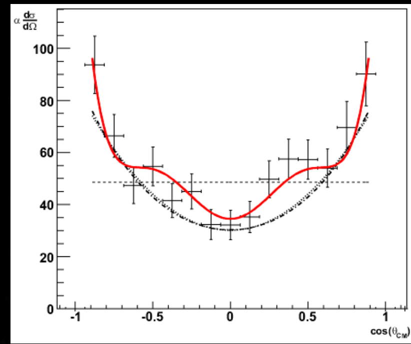
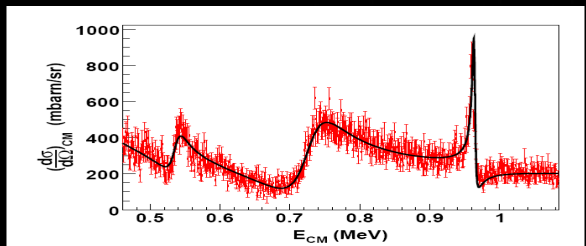
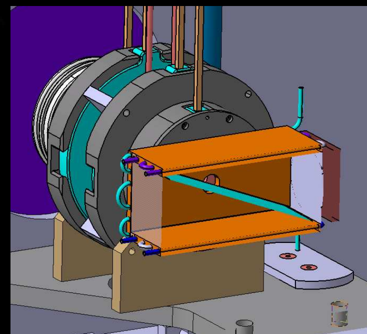
Explosive hydrogen burning studied with RIB





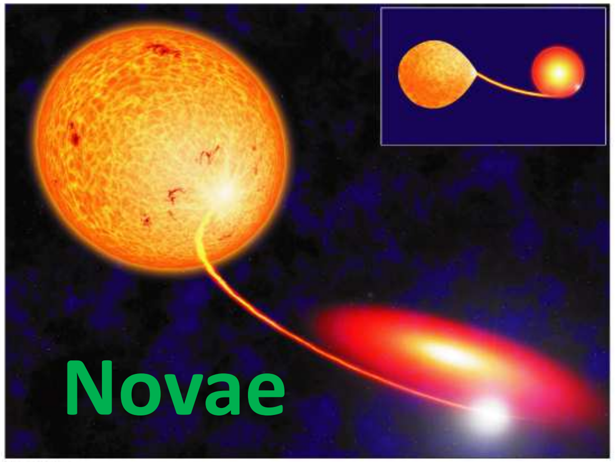






GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

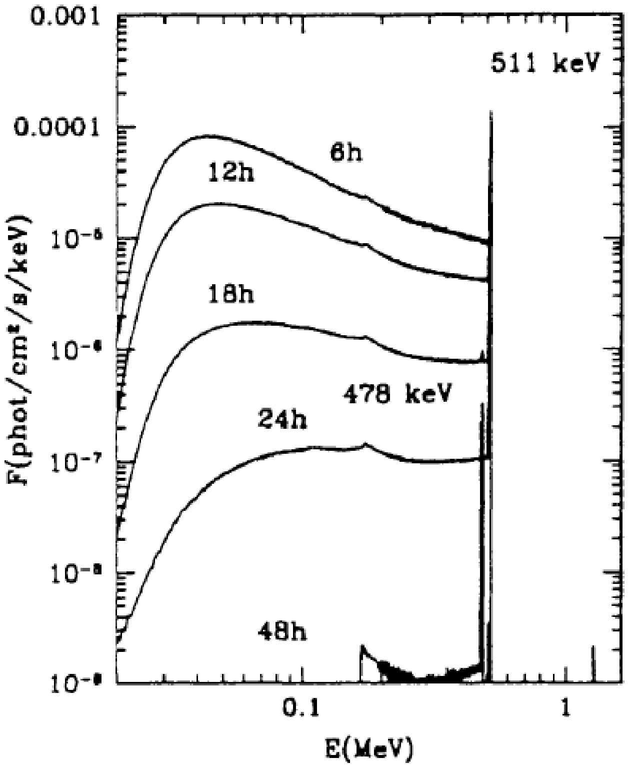
F. de Oliveira Santos



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

γ-ray astronomy

Predictions – Hernanz et al.



Models say that overall novae gamma-ray emission is *dominated by 511 keV γ-rays from ^{18}F β+ decay*

- Need to know rates of reactions creating and destroying ^{18}F

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

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

Inelastic scattering and p-p correlation

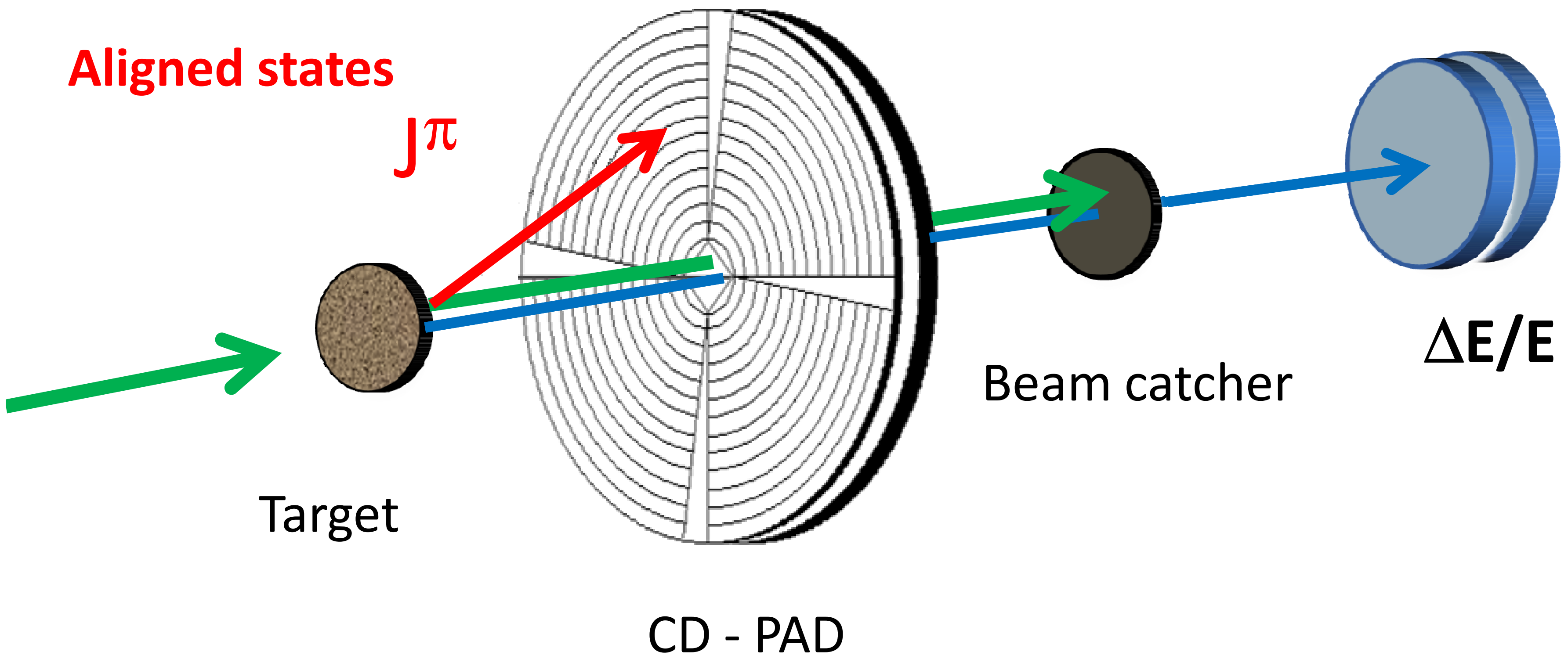
LLN

8 10^7 pps

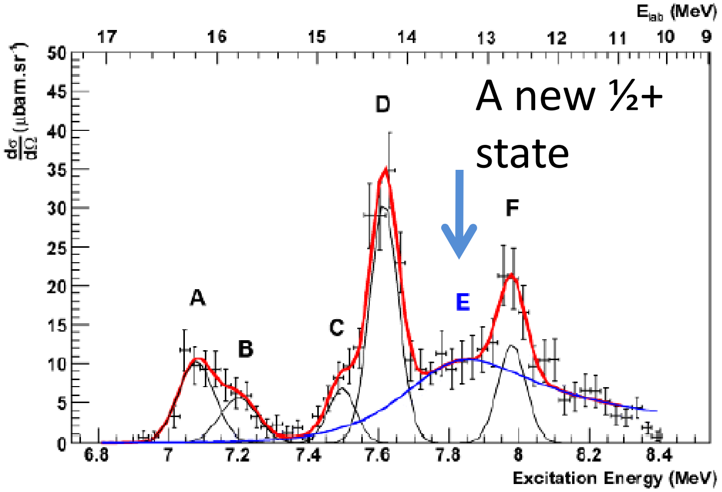
$^{19}Ne + {}^{1}H \longrightarrow p + {}^{19}Ne^*$

↳ $^{15}O + \alpha$

↳ $^{18}F + p$



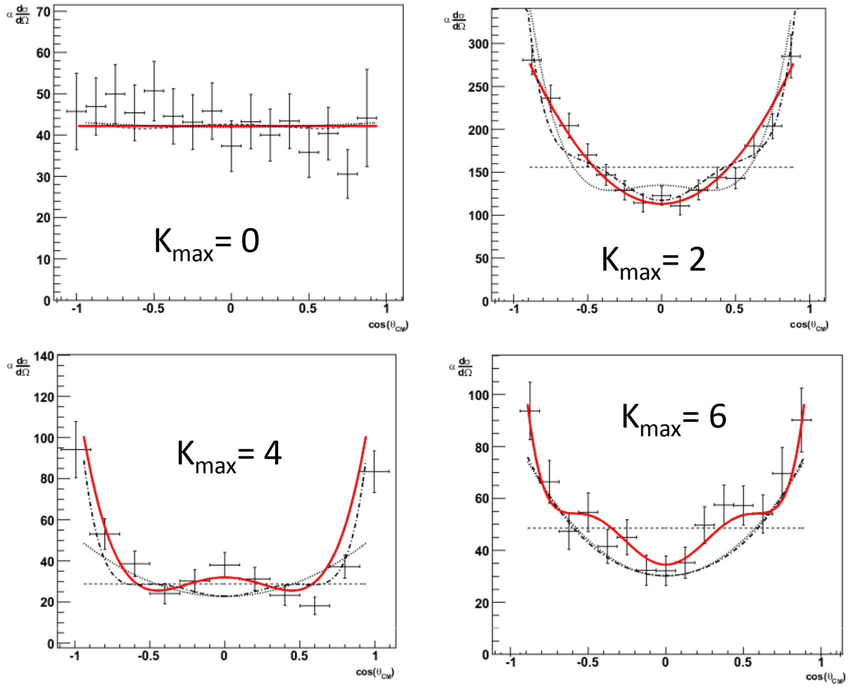
$H(^{19}Ne,p')^{19}Ne^{*}(p)^{18}F$



This new 1/2+ state was predicted by

Dufour and Descouvemont NPA 785, 381 (2007)

New Spin Assignments

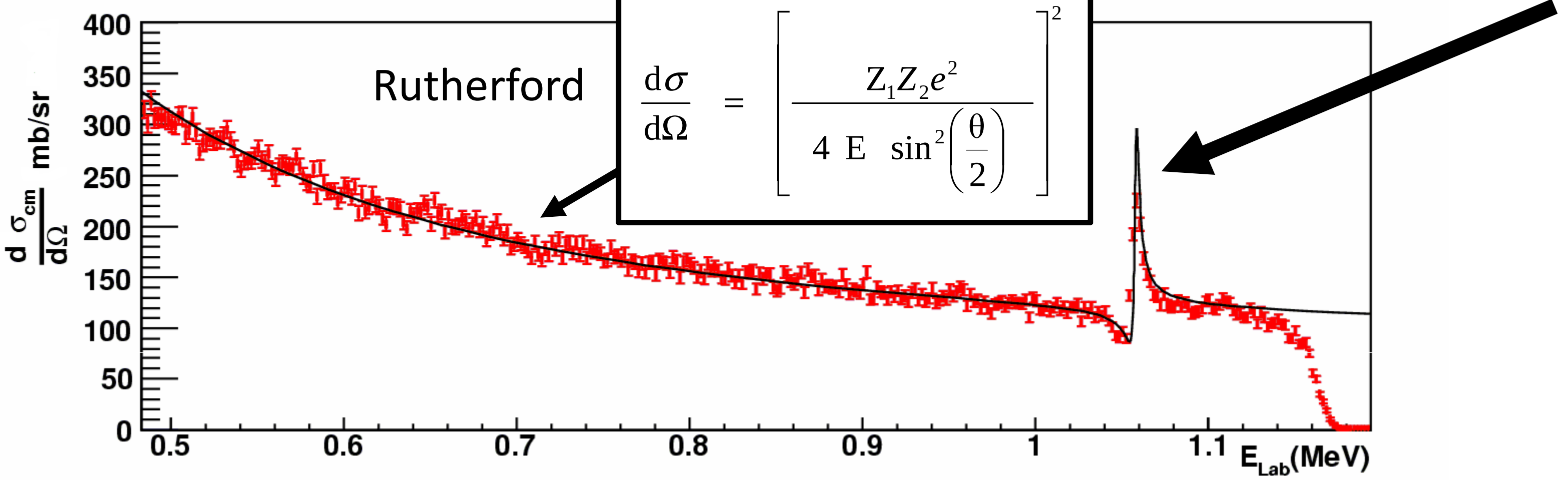


	This experiment				Previous measurements			
Label	E_r(keV)	E_x(MeV)	Γ (keV)	J^π	E_x(MeV)	Γ (keV)	J^π	ref
A	669(5)	7.079(5)	32(8)	$\frac{3}{2}^{(+)}$	7.075(1.6)	39(2.2)	$\frac{3}{2}^{+}$	[7]
B	793(31)	7.203(31)	35(12)	$\frac{3}{2}^{(+)}$	7.173(5)	-	-	[5]
					7.238(6)	-	-	[5]
C	1092(30)	7.502(30)	17(7)	$\frac{5}{2}^{(-)}$	7.500(9)	16(16)	-	[5]
					7.531(11)	31(16)	-	[5]
D	1206(5)	7.616(5)	21(10)	$\frac{3}{2}^{(+)}$	7.608(11)	45(16)	$\frac{3}{2}^{+}$	[17]
					7.644(12)	43(16)		[5]
E	1452(39)	7.863(39)	292(107)	$\frac{1}{2}^{(+)}$	-	-	-	
F	1564(10)	7.974(10)	11(8)	$(\frac{5}{2}^{-})$	7.944(15)	-	-	[18]
					8.069(12)	-	-	[18]

J.C. Dalouzy et al. Phys. Rev. Lett. 102, 162503 (2009) PhD 2008 Université de Caen

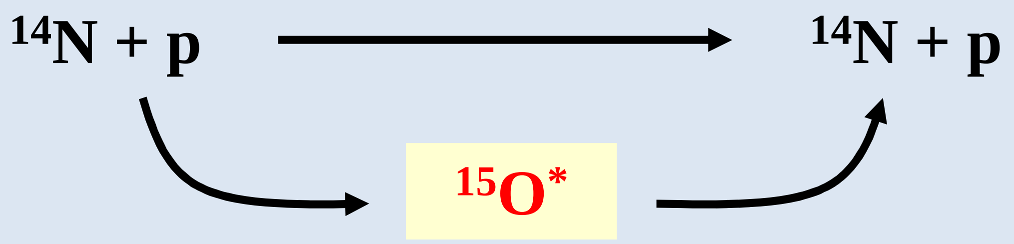
Resonant Elastic Scattering

Excitation function for: **p + ^{14}N ⇒ p + ^{14}N**



$$\frac{d\sigma}{d\Omega} = \left[\frac{Z_1 Z_2 e^2}{4\ E\ \sin^2\left(\frac{\theta}{2}\right)}\right]^2$$

Two contributions : (Wentzel 1934)



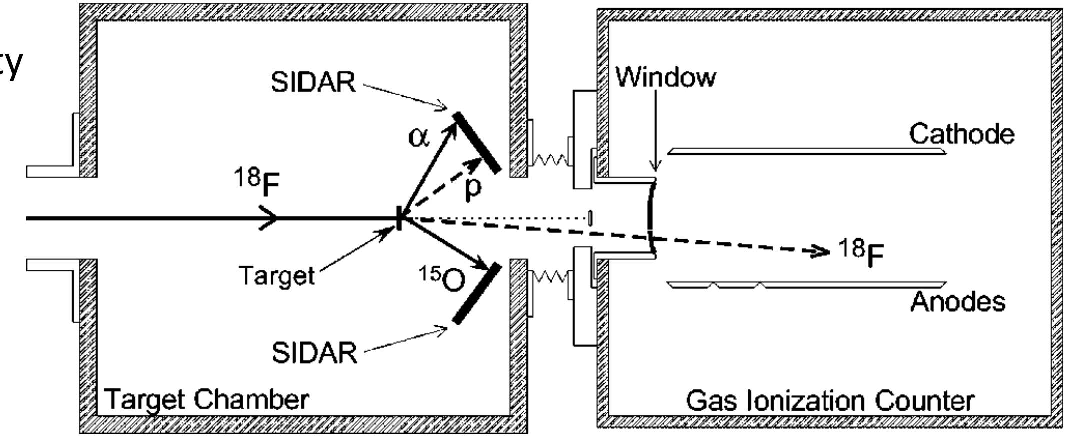
Compound nucleus

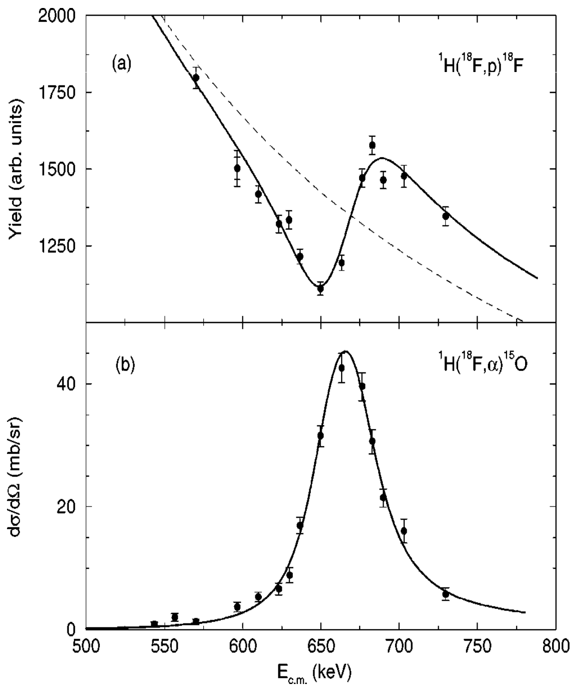
(thesis Iulian Stefan GANIL 2007)

ORNL Holifield Radioactive Ion Beam Facility

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

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





Direct measurement

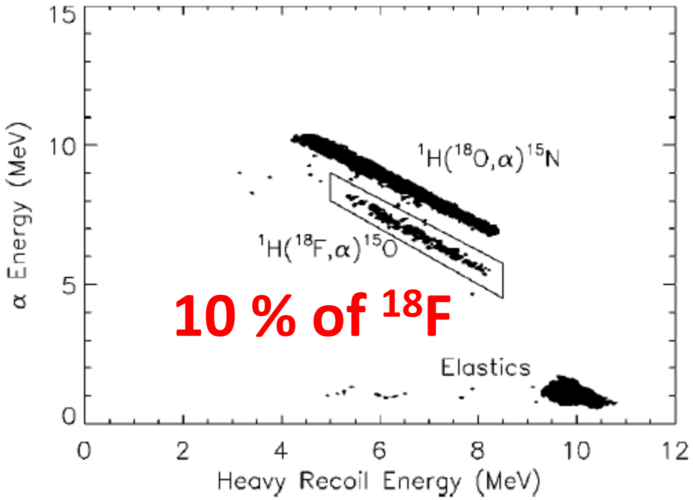
$E_x = 7076 \pm 2$ keV

$\ell = 0$

$\Gamma = 39.0 \pm 1.6$ keV

$\Gamma_p/\Gamma = 0.39 \pm 0.02$

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

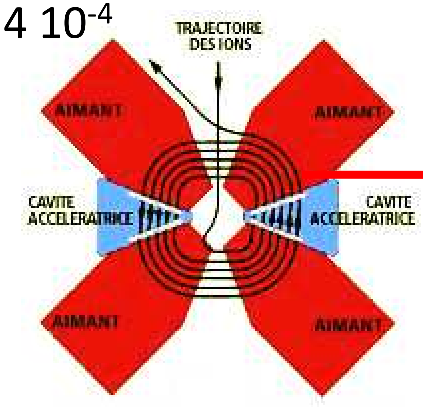


Beam polluted

Alex Murphy et al University of Edinburgh

GANIL
GRAND ACCELERATEUR NATIONAL D'IONS LOURDS

CIME Resolving power
$\Delta M / M \sim 4\ 10^{-4}$



$^{18}F^{4+}$
$^{18}O^{4+}$ ~ 2nAe
$^{18}Ne^{4+}$

stripper
8.4 µm of Al
60 µg/cm² of C

$^{18}F^{9+}$ 97 % 4 AMeV
$^{18}Ne^{9+}$ 3%
$\Delta M / M \sim 2\ 10^{-4}$

Z spectrometer

MCP

2 10^4 pps

degrader

Au
6 µm

target

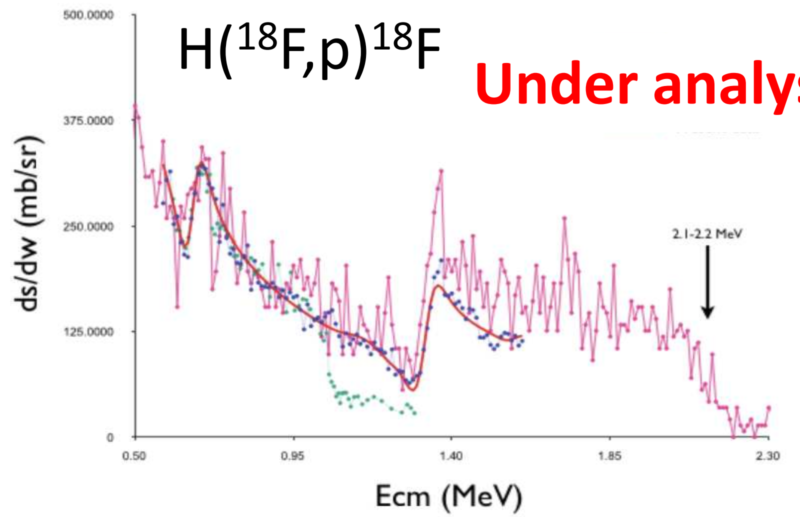
CH2
50 µm

E ~ 2.3 AMeV

DSSD

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

Under analysis



^{18}F+p resonance properties

TABLE I. Resonance parameters in ^{19}Ne vs ^{19}F.

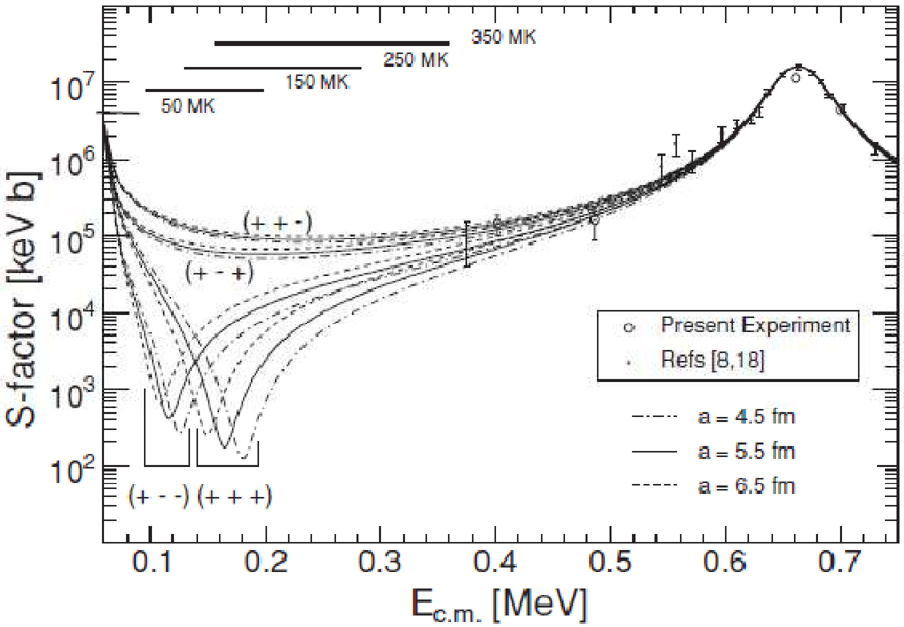
^{19}F					^{19}Ne								Ref.
E_x (MeV)	J^π	Γ_γ (eV)	Γ_α (keV)	Γ_{tot} (keV)	No	E_x[a] (MeV)	E_r (keV)	J^{π}[b]	Γ_γ[c] (eV)	θ_p^2[d]	Γ_p[d] (keV)	Γ_α[e] (keV)	
6.497	$\frac{3}{2}^+$	0.85	<0.5	<0.5	1	6.419	8(6)	$(\frac{3}{2}^+)$	0.77(41)	0.12(2)	2.2(4)E−37	0.27(27)	[17,19–23,29,32]
6.500	$\frac{11}{2}^+$	0.38	>2.4 eV	>2.4 eV	2	(6.422)	11(30)	$(\frac{11}{2}^+)$	0.35(18)	(0.1)	1.8(18)E−38	20(14)E−3	[32]
6.536	$\frac{1}{2}^-$	–	245	245	3	6.437	26(9)	$\frac{1}{2}^-$	[1(1)]	0.01	1.1(11)E−20	220(20) (M)	[6,17,29,32]
6.528	$\frac{3}{2}^+$	1.2	1.2	1.2	4	6.449	38(7)	$(\frac{3}{2}^+)$	1.1(6)	0.03(3)	4(4)E−15	1.3(10)	[17,20–22,25,29,32]
6.554	$\frac{7}{2}^+$	0.16	1.6	1.6	5	(6.504)	93(30)	$(\frac{7}{2}^+)$	0.14(8)	(0.1)	4.6(46)E−10	0.4(4)	[29,32]
6.592	$\frac{9}{2}^+$	0.33	7.3 eV	7.6 eV	6	(6.542)	131(30)	$(\frac{9}{2}^+)$	0.30(16)	(0.1)	2.7(27)E−12	1.3(11)E−2	[32]
6.838	$\frac{5}{2}^+$	0.33	1.2	1.2	7	6.698	287(6)	$(\frac{5}{2}^+)$	0.29(15)	0.01	1.2(12)E−5	1.2(10)	[17,22,25,29,32]
6.787	$\frac{3}{2}^-$	5.5	4.3	4.3	8	6.741	330(6)	$\frac{3}{2}^-$	5.0(26)	–	2.22(69)E−3	5.2(37)	[17,25,29,32]
6.891	$\frac{3}{2}^-$	3.1	22	22	9	(6.841)	430(30)	$(\frac{3}{2}^-)$	2.8(15)	(0.01)	9.7(97)E−3	25(18)	[17,29,32]
6.927	$\frac{7}{2}^-$	2.4	0.9	0.9	10	6.861	450(6)	$\frac{7}{2}^-$	2.3(12)	(0.01)	1.1(11)E−5	1.2(0.9)	[17,29,32,44]
6.989	$\frac{1}{2}^-$	–	96	96	11	(6.939)	528(30)	$(\frac{1}{2}^-)$	[1(1)]	(0.01)	3.4(34)E−2	99(69)	[29,32]
7.114	$\frac{5}{2}^+$	–	25	25	12	(7.054)	643(30)	$(\frac{5}{2}^+)$	[1(1)]	(0.1)	4.7(47)E−2	29(25)	[29,32]
(7.300)	$\frac{3}{2}^+$	–	–	–	13	7.0757	664.7(16)	$\frac{3}{2}^+$	[1(1)]	–	15.2(1)	23.8(12) (M)	[18,24,29]

M = measured alpha widths, others from mirror or assumed

Large uncertainties remain !

C.D.Nesareja *et al.*, Phys. Rev. C75 (2007) 055809

Astrophysical *S*-factor for $^{18}F(p,a)$ reaction

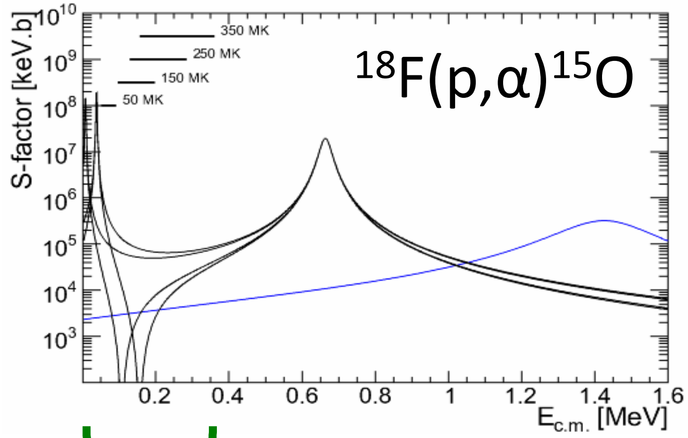


N. de Séréville *et al*., Phys. Rev. C79 (2009) 015801

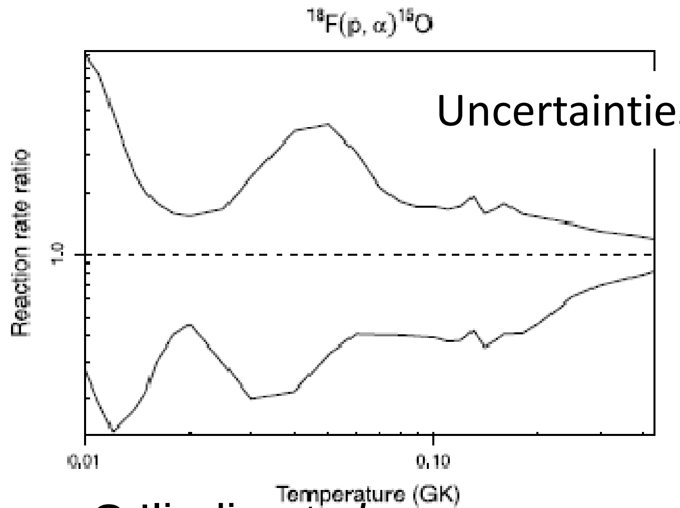
Large uncertainties due to the unknown signs of interferences.

The signs of the interferences cannot be predicted, neither measured indirectly.

➡ Direct measurement required

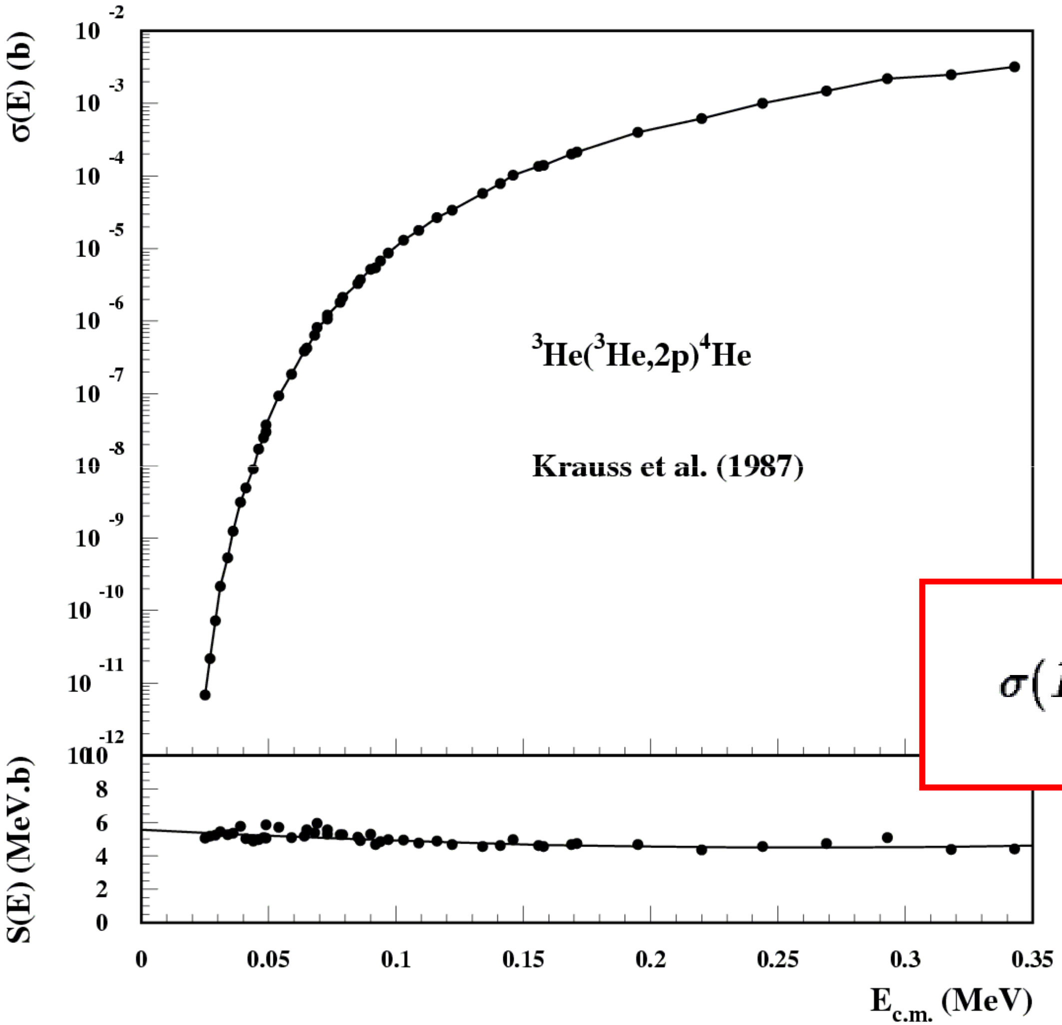


Limited effects of the interferences due to the tail of the ½+ resonance



C.Iliadis *et al.*,
Nucl. Phys. A841 (2010) 31

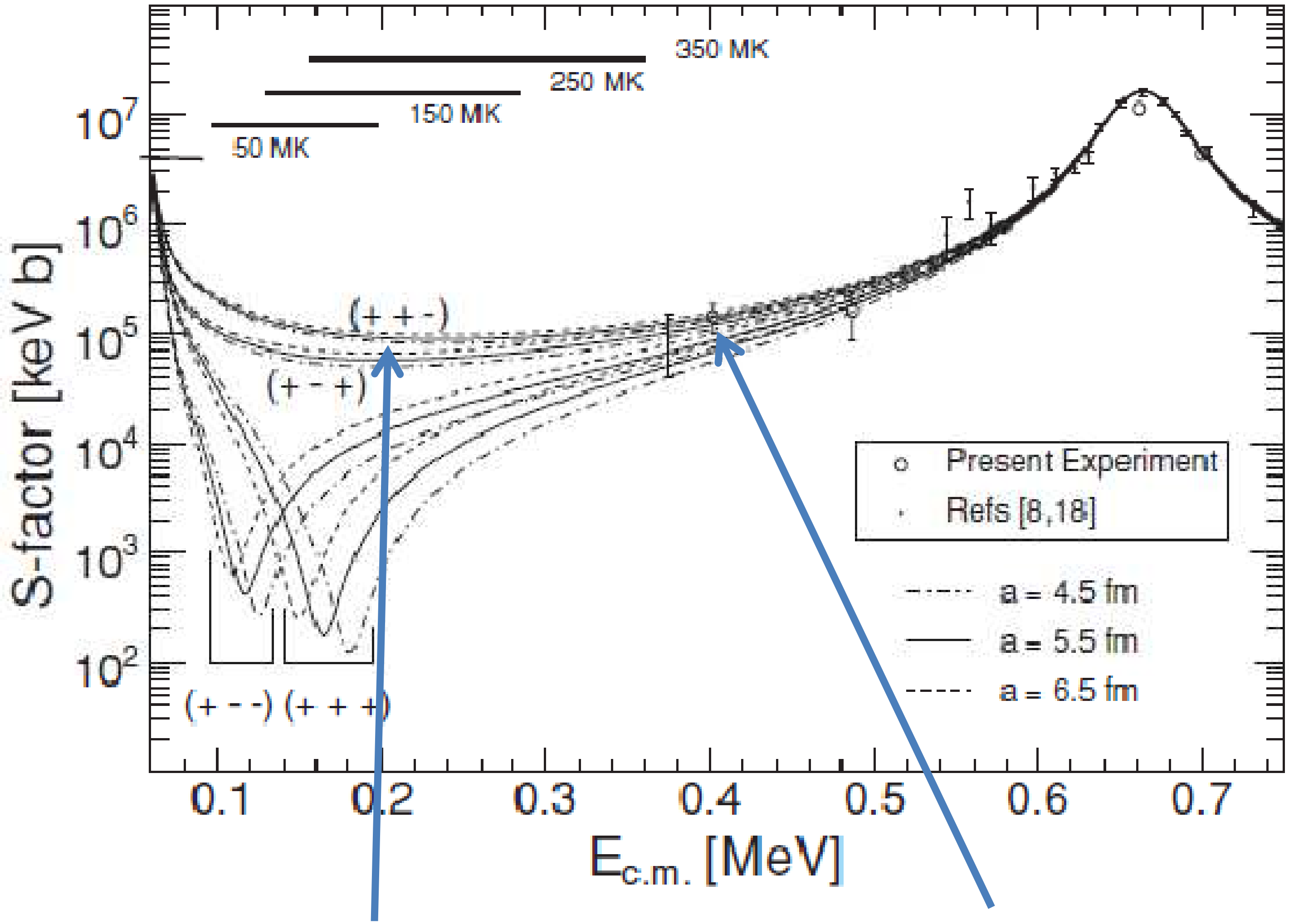
Astrophysical S Factor



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

(C. Rolfs Cauldrons in the cosmos)

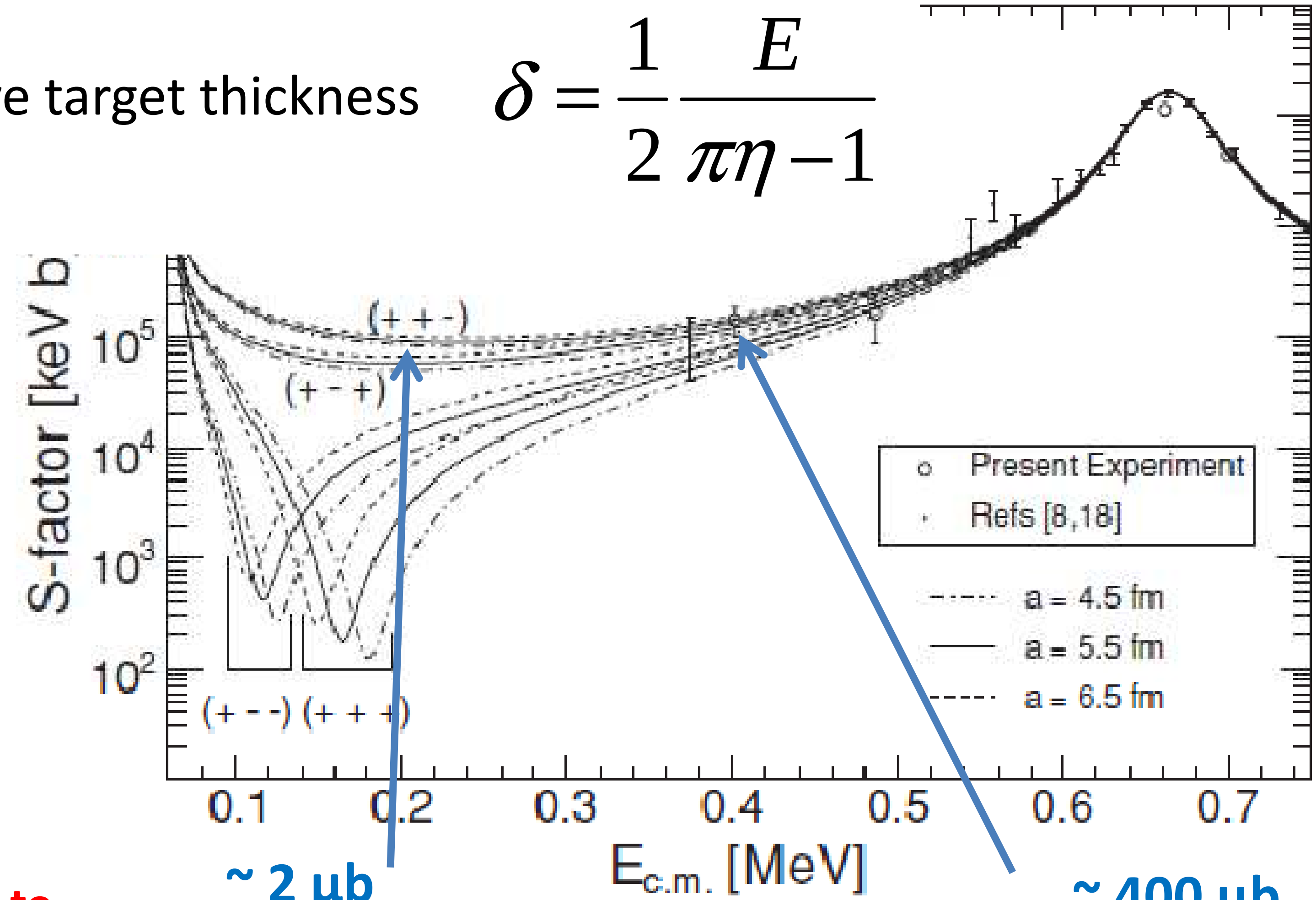
Required beams for direct measurement



~ 2 μb **~ 400 μb**

Required beams for direct measurement

Effective target thickness $$\delta = \frac{1}{2}\frac{E}{\pi\eta - 1}$$



In order to get 10 counts/day

~ 2 μb
11 keV
$3\ 10^8$ pps

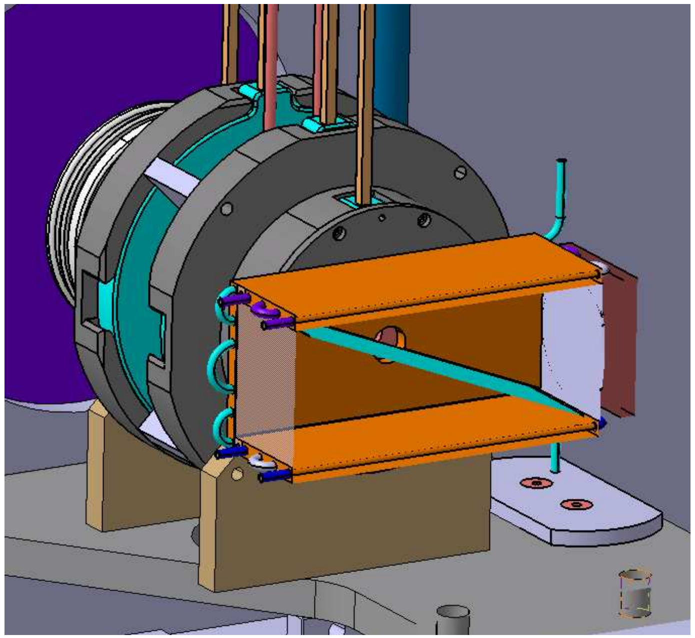
~ 400 μb
34 keV
$5\ 10^5$ pps

High intensity beams

For 1 mA of ^{3}He@35 MeV
35 kW

^{14}O Production ~ 2 10^{11} pps

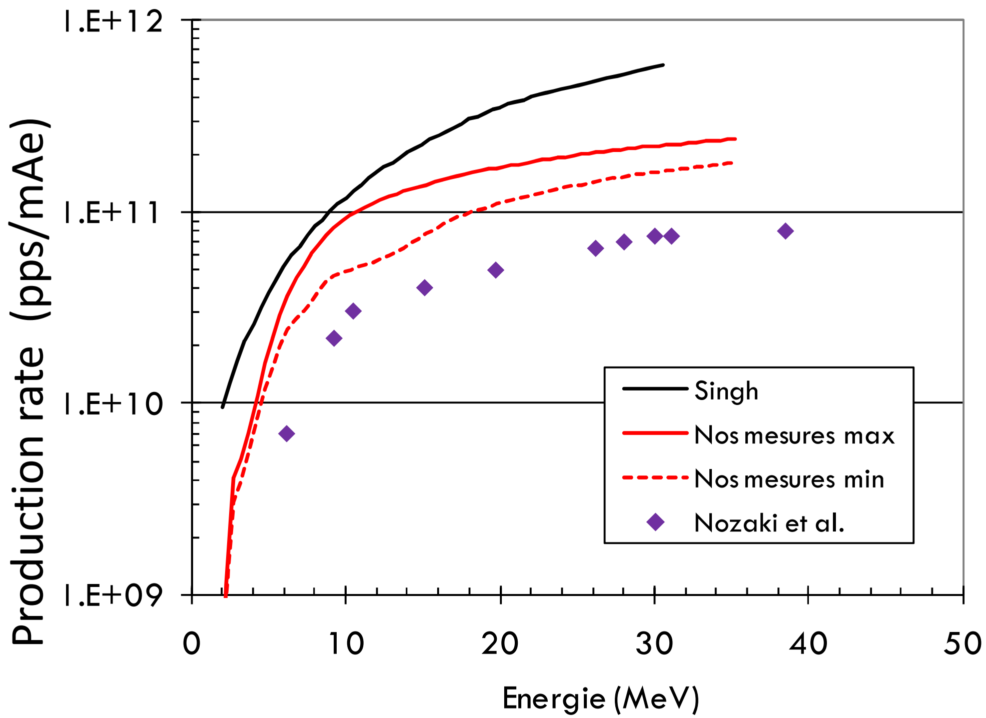
More than 100 times the SPIRAL1 intensity @ 1.5 kW



$^{12}C(^3He,n)^{14}O$
cross section
Measured at Rez (CZ)

GANIL, Soreq, Weizmann Inst.,
+ CENBG SP2 PP

Production rate of ^{14}O



SPIRAL2 beams

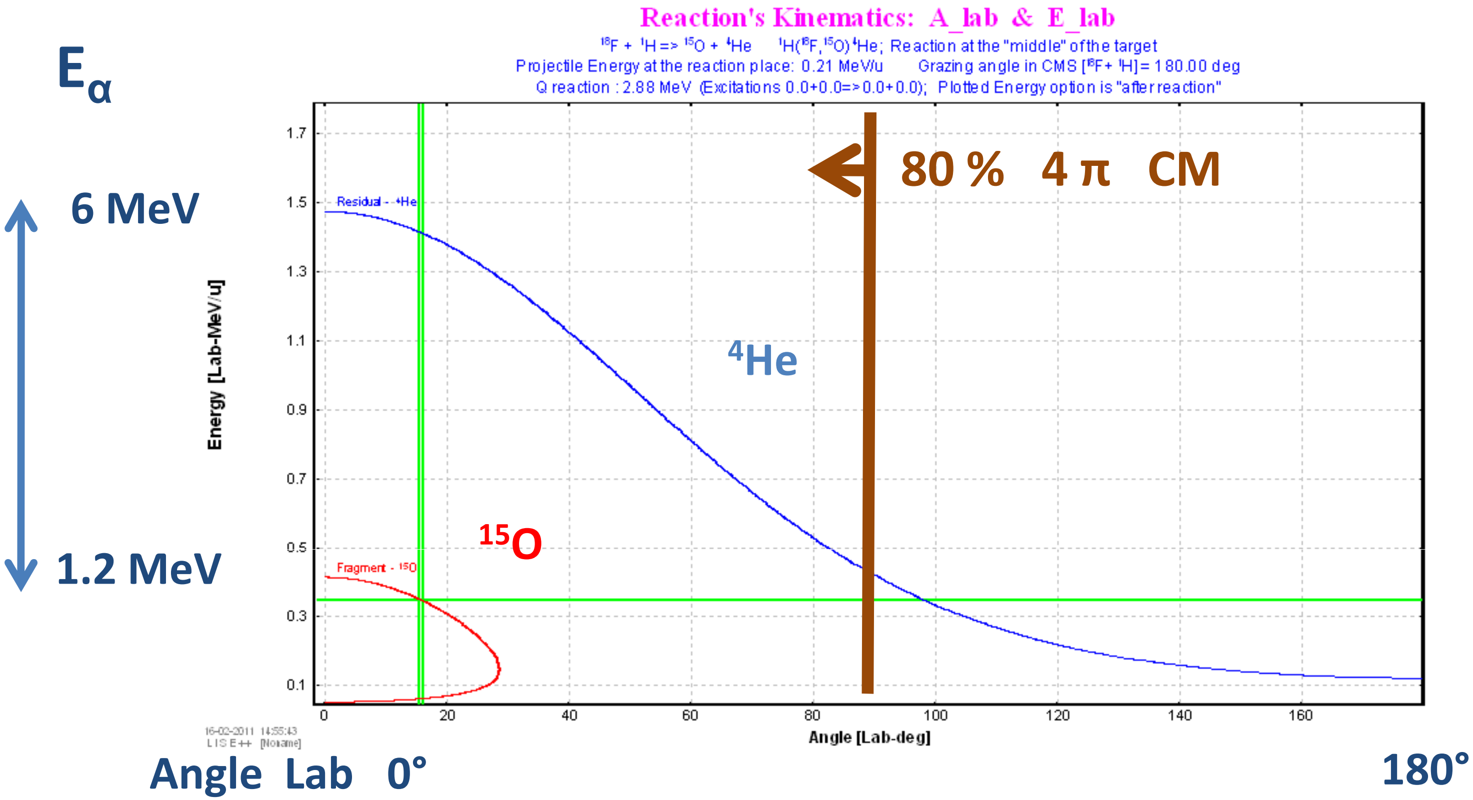
From Report N°1 WP7.1 SP2 PP

Product	Reaction	Threshold MeV	Target and comments
	$^{14}N(p,2n)$	31.2	useful range idem
^{18}F 110 m	$^{15}N(\alpha,n)$ $^{16}O(^{3}He,p)$	8.1 0	BN 0.36%, too low abundance of N oxide
^{17}F 64.8 s	$^{14}N(\alpha,n)$ $^{16}O(d,n)$ $^{16}O(^{3}He,d)$	6.1 1.8 5.8	BN, nothing known about release of fluorine oxide, risk of combination with other element than oxygen alternative to previous
^{19}Ne 17.2 s	16 19		
^{18}Ne 1.7 s	16 16 19		

Day1_SPIRAL2_Phase2

Isotope	Half life		E_{nom} /A·MeV	$I(E_{nom})$ /pps	E_{min} /A·MeV	$I(E_{min})$ /pps	E_{max} /A·MeV	$I(E_{max})$ /pps
6He	806.7	ms	7.4	7.0E+09	1.8	7.0E+09	24.9	N. E.
8Li	840.3	ms	16.6	N. E.	4.1	7.1E+08	24.9	N. E.
14O	70.598	s	21.6	1.3E+07	5.4	1.3E+07	24.8	1.3E+06
15O	122.24	s	18.9	8.3E+07	4.7	8.3E+07	24.8	8.3E+06
18F	109.771	m	13.2	1.3E+07	3.3	1.3E+07	24.8	1.3E+06
18Ne	1.672	s	20.5	7.4E+07	5.1	7.5E+07	24.8	7.4E+06
23Ne	37.24	s	12.6	2.4E+08	3.1	2.4E+08	24.8	2.4E+07

Required beams for direct measurement



Beam: ^{18}F

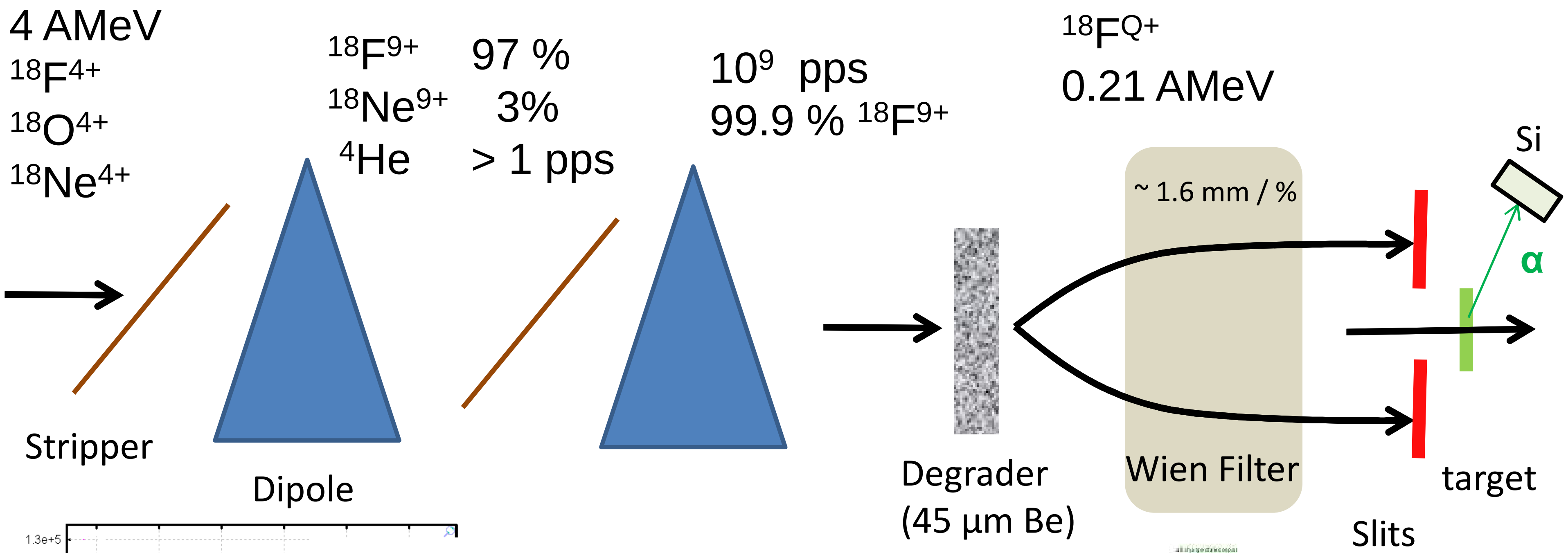
Purity: 100 % ?? A major issue

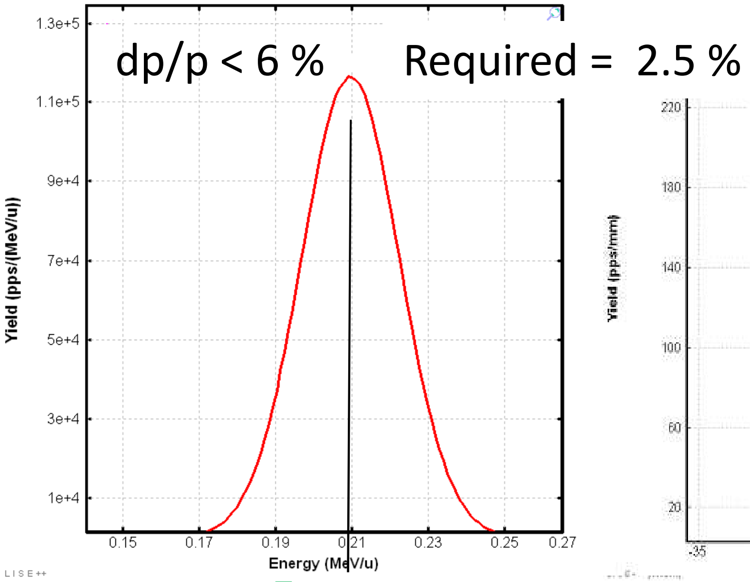
Energy: 0.21 AMeV (200 keV in CM)

Target: thin plastic foil

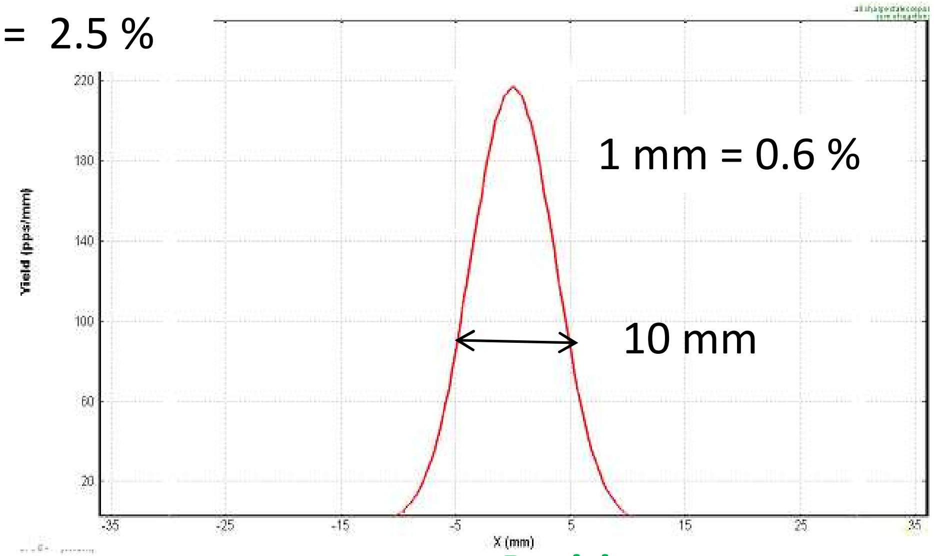
Angular distribution is required – not uniform angular distribution

Purification and Energy settings





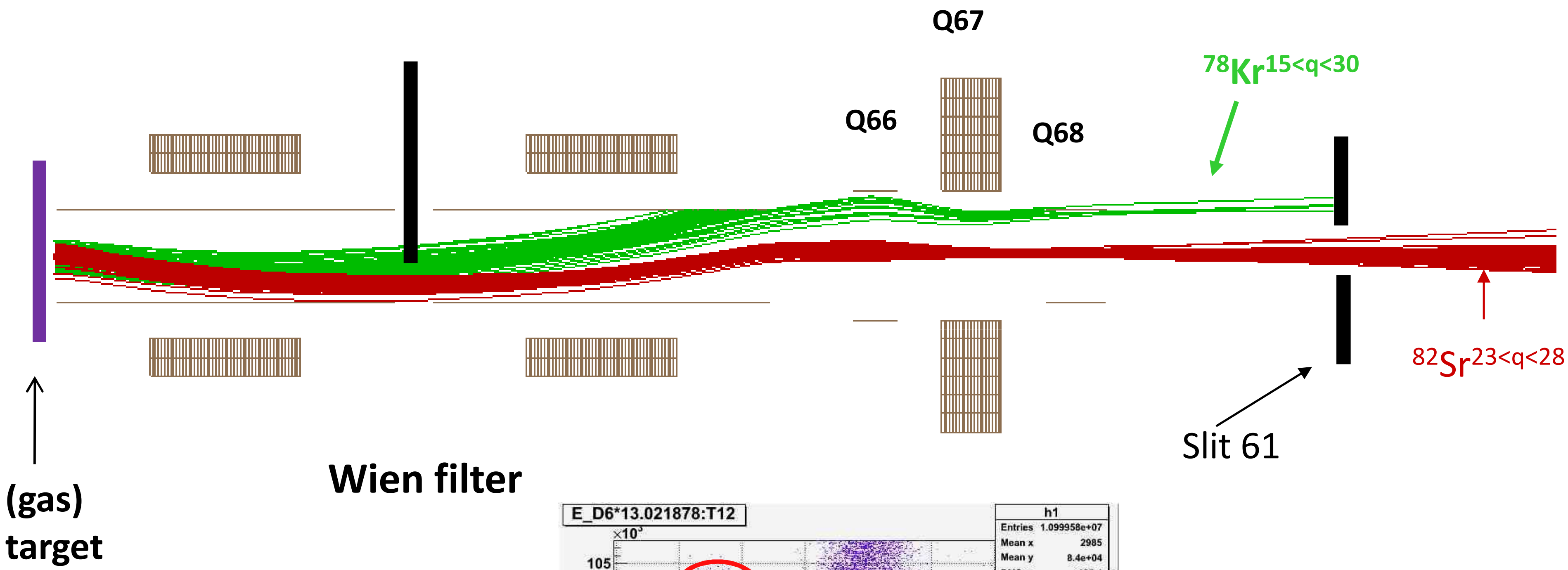
Energy

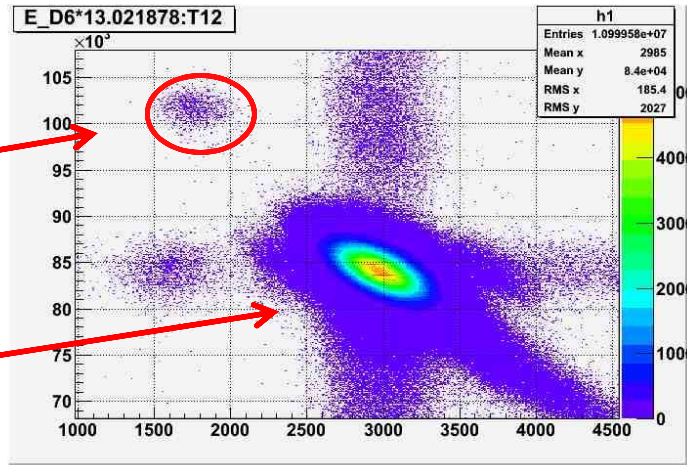


Position

(α,γ) reactions

A test experiment was performed with $^{78}Kr(\alpha,\gamma)^{82}Sr$ (p process)



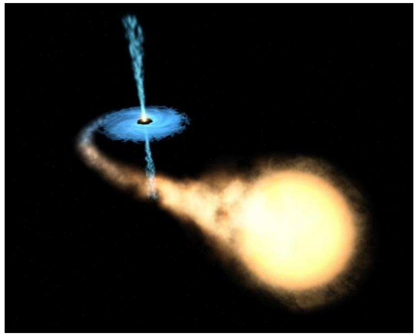


Primary beam
Measured Rejection ~ 10^{10}

Degraded Primary beam
(inhomogeneities of the target)

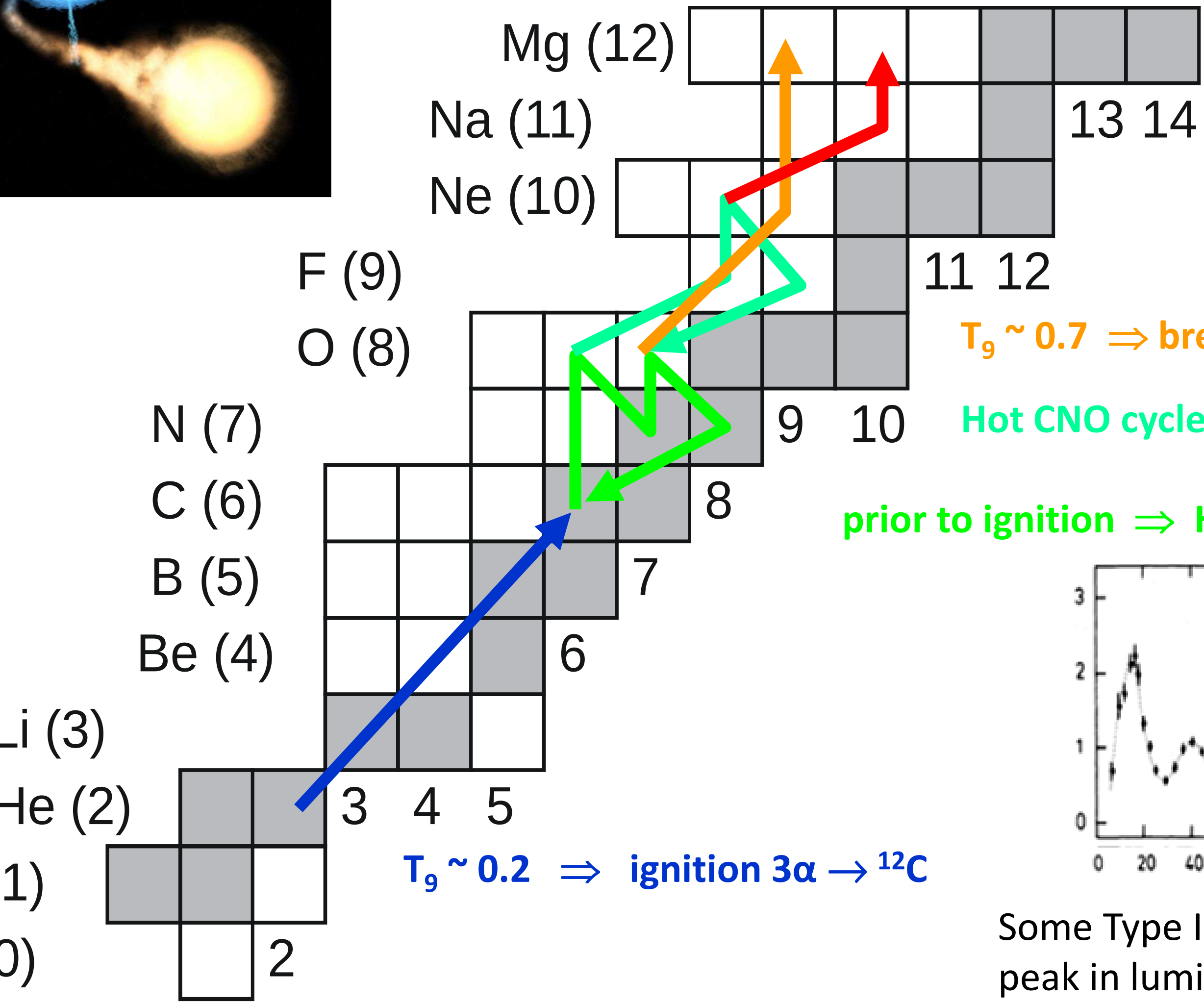
P. Ujic Ph. D. GANIL
E563 S. Harrisopoulos

X-ray Bursts



$T_9 \sim 0.8 \Rightarrow$ **breakout 2: $^{18}Ne(\alpha,p)^{21}Na$**

(~50 ms after breakout 1) leads to *rp*-process and main energy production



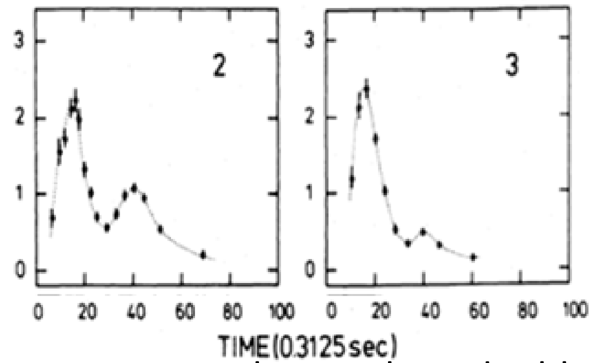
$T_9 \sim 0.7 \Rightarrow$ **breakout 1: $^{15}O(\alpha,\gamma)^{19}Ne$**

Hot CNO cycle II

prior to ignition $\Rightarrow$ Hot CNO cycle

$T_9 \sim 0.2 \Rightarrow$ **ignition $3\alpha \rightarrow {}^{12}C$**

courtesy: H. Schatz, T. Davinson



Some Type I X-ray bursts show double peak in luminosity separated by a few seconds origin of double-peak structures still controversial

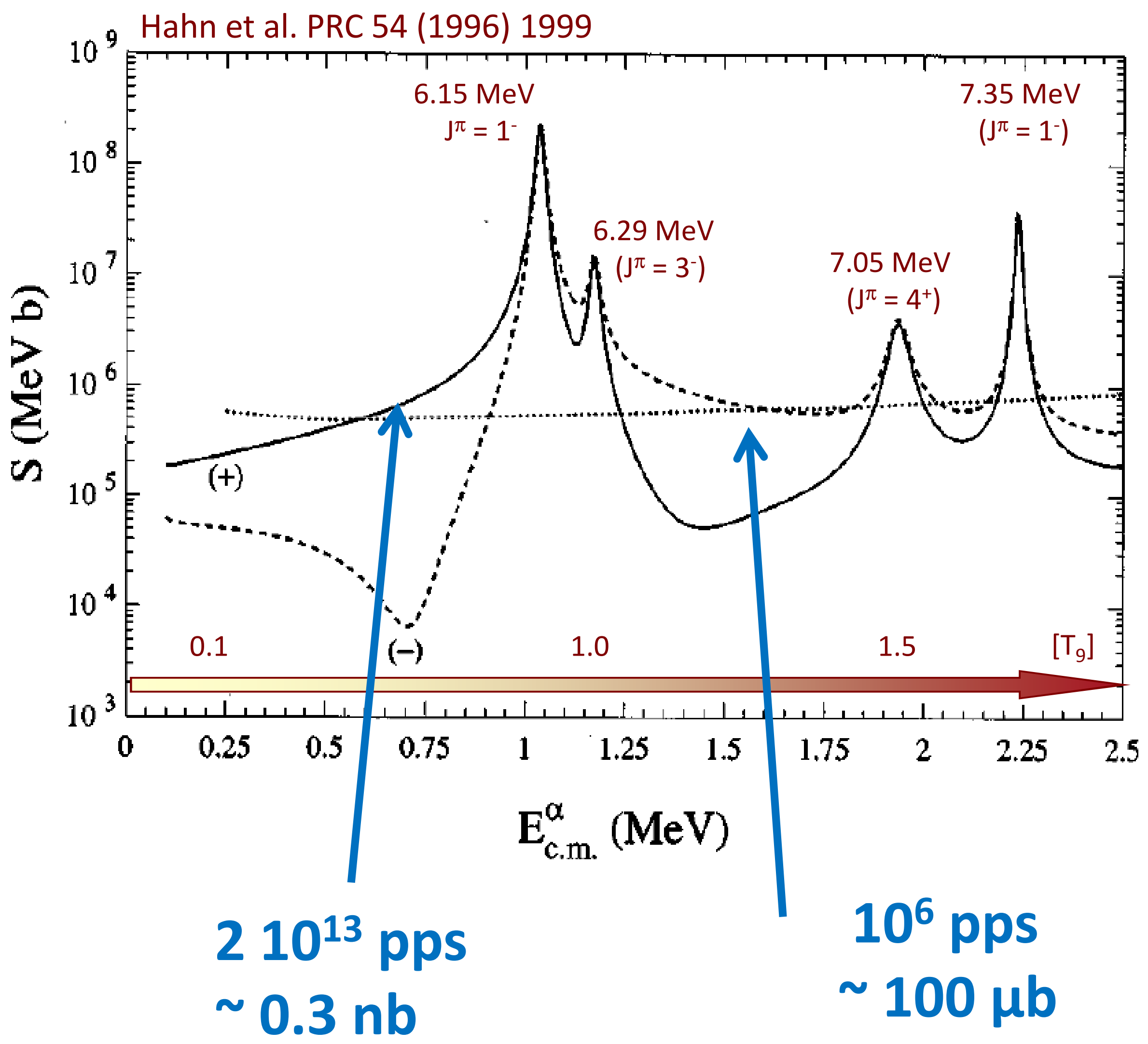
Szatjano et al. ApJ 299 (1985) 487-495

$^{14}O(\alpha,p)^{17}F$ reaction – breakout from HCNO

Resonant Breit-Wigner contributions + direct capture + interference

Funck et al. NP A 480 (1988) 188, ZPhys A 332 (1989) 109

Microscopic calculations (dotted line)

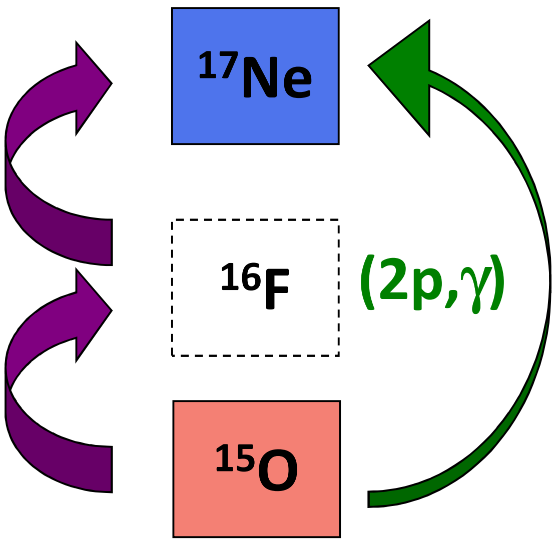


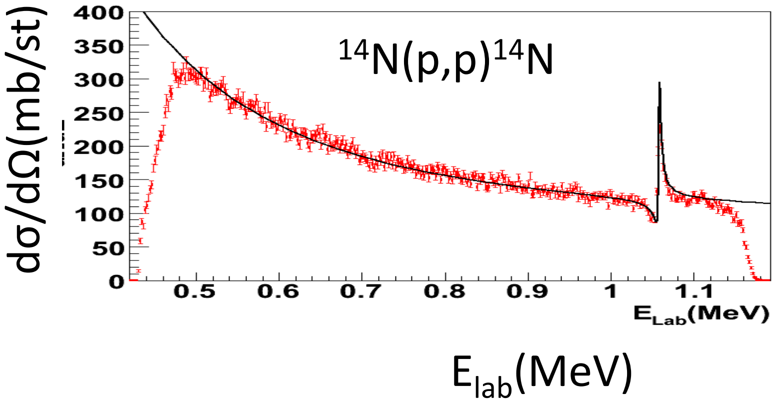
Time reverse reaction $^{17}F(p,\alpha)^{14}O$ can be used to determine the reaction rate but it is limited.

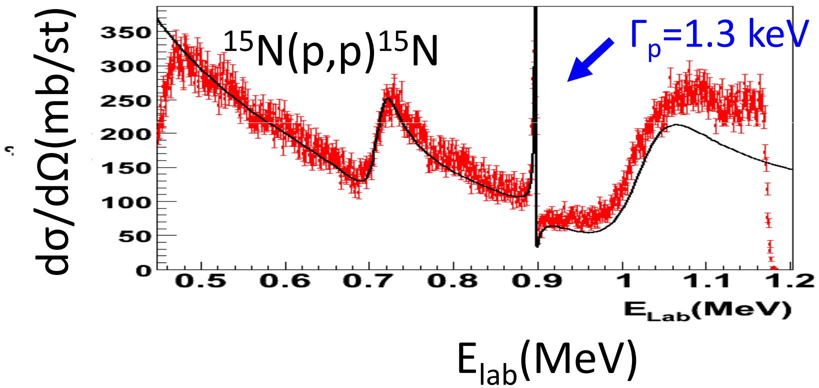
Alternatives reactions $^{15}O(2p,\gamma)^{17}Ne$

$^{15}O(2p,\gamma)^{17}Ne$

J. Gorres *et al.*, Phys. Rev. C51, 392 (1995)
L. Grigorenko et al., Phys. Rev. C72, 015803 (2005)

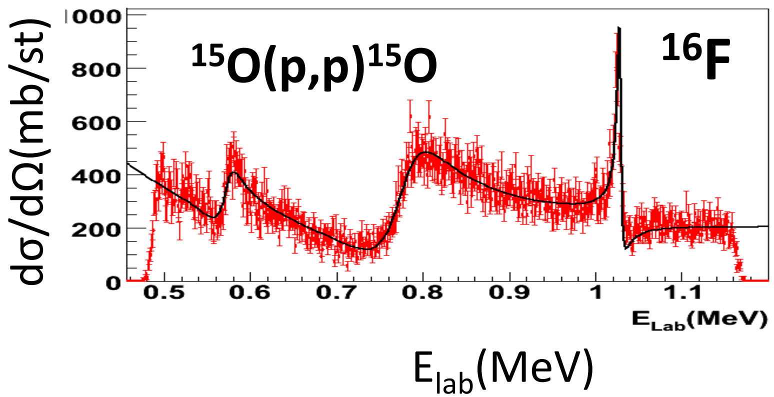






^{15}O 1.2 AMeV

10^6 pps



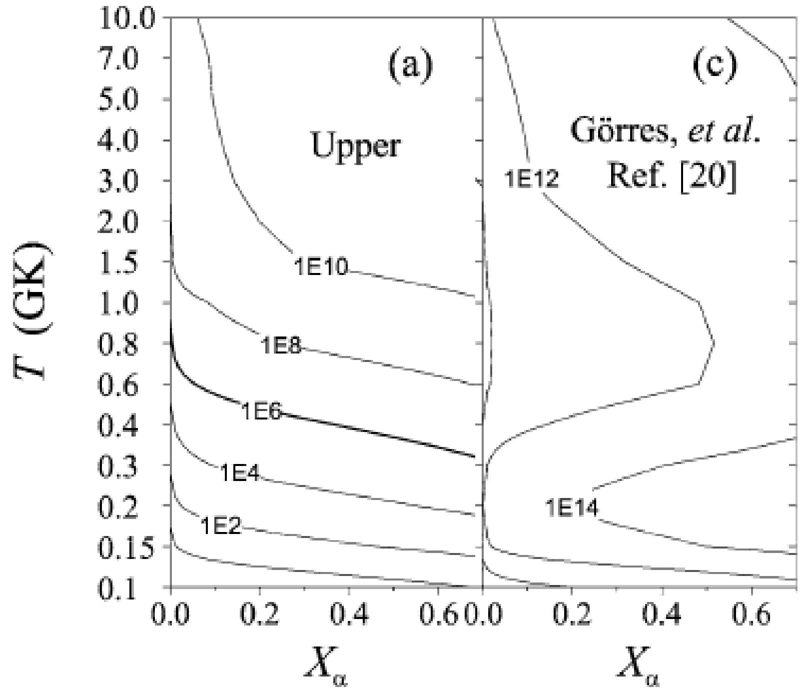
Iulian Stefan Thesis 2007
Tours 2006, Procon 2006
Eprint: nucl-ex/0603020

Alternatives reactions $^{15}O(2p,\gamma)^{17}Ne$

TABLE I: Measured properties for the low-lying states in ^{16}F.

E_{CM} (keV)^b	E_x (keV)^a	E_x(keV)^b	J^π	Γ_p (keV)^a	Γ_p (keV)^b
534 ± 5	0	0	0^-	40 ± 20	25 ± 5
732 ± 10	193 ± 6	198 ± 10	1^-	< 40	70 ± 5
958 ± 2	424 ± 5	425 ± 2	2^-	40 ± 30	6 ± 3

^{a}Recommended values [14]
^{b}This work.



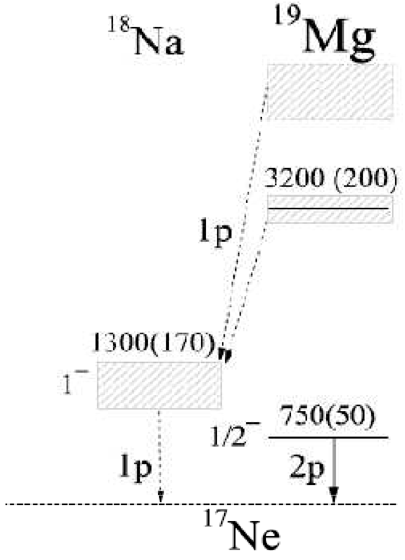
Other channel ??

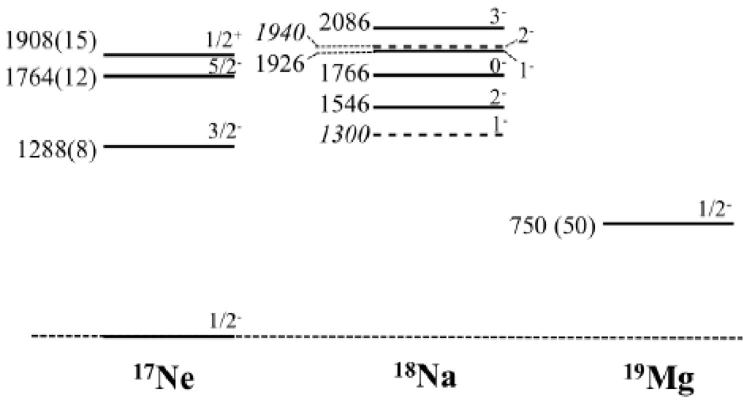
$p+p \Leftrightarrow {}^2He$

${}^2He + {}^{15}O \rightarrow {}^{17}Ne + \gamma$

To be studied with a two-proton transfer reaction (LoI Marlene Assié / SPIRAL2)

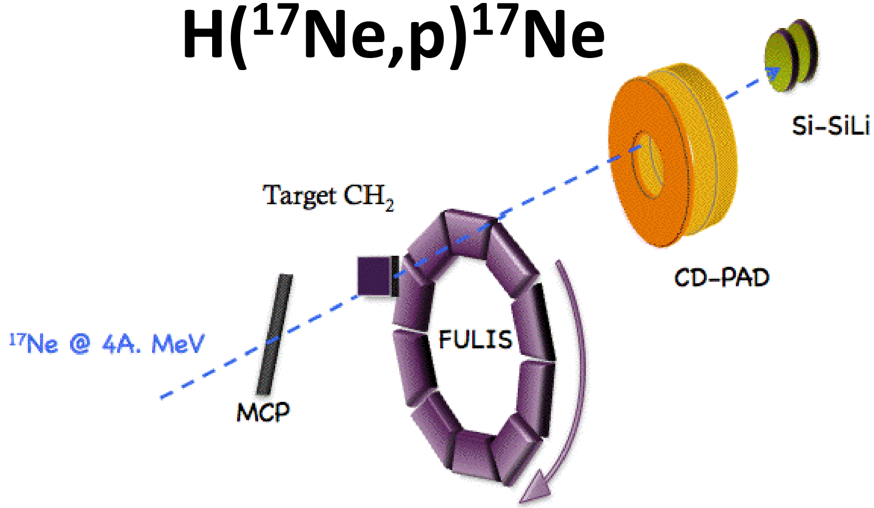
I. Mukha *et al*, PRL (2007)
I. Mukha et *al* , PRC (2008)

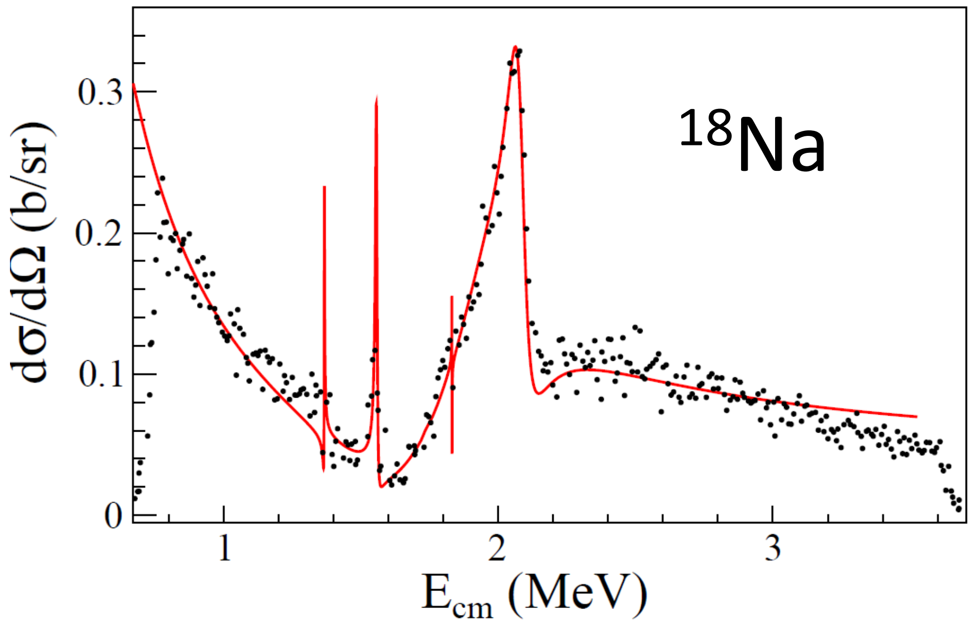




$T^{meas}_{1/2}$ = 4.0(15) ps
$T^{cal}_{1/2}$ ~ 2 ps

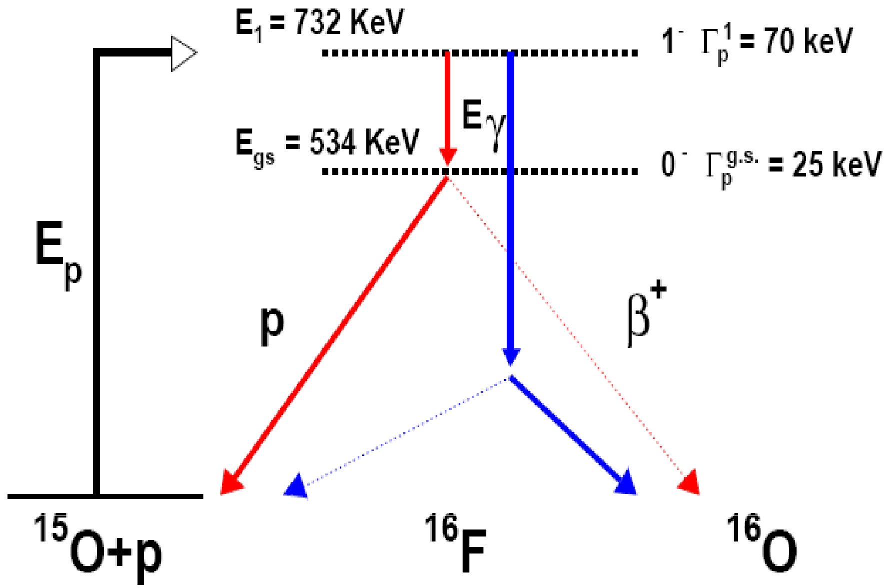
H(^{17}Ne,p)^{17}Ne





To be submitted   M. Assié et al.

Exotic reaction mechanism



$T_{1/2}\,(\gamma) \sim 10^{-12}$ s

We used

$$\sigma_{(p,\gamma)(\beta^+)} = \int \sigma_{(p,\gamma)}(E_p, E_\gamma) P_\gamma(E_\gamma) P_{\beta^+}(E_p, E_\gamma) dE_\gamma$$

BW Cross-section to capture a proton with the energy Ep and to emit a gamma with the energy Eγ

Density of the ^{16}F gs

β+ branching ratio

σ ~ 0.1 nb

Summary

Final word of reaction rates → direct measurements

Novae, X-Ray Bursters are Explosive environments T9 > 0.1

Gamow window ~ 0.1 – 1 MeV

σ > 1 μb (in a large range of energy)

Reachable with RIB intensities > 10^8 pps

+ New reactions mechanisms

EURISOL Design Study ??