The Application of R-Matrix analysis to experimental data: 2 - Reaction Rates

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Outline of talk

- Introduction
- Why do we spend so much effort on ^{19}Ne?
- Why is it so hard?
- How can we use R-matrix to help?
- Future programme

Introduction

'Observational' data

- satellite observations of γ-rays, e.g. ^{26}Al, ^{44}Ti
- isotopic ratios in grains
- light curves (powered by radioactive decay)
- (abundances from stellar spectra)

Isotopic data gives information on

✓ Nucleosynthesis

✓ Stellar conditions

✓ Astrophysical processes

✓ Explosion mechanism

⇒ **Need to know the nuclear physics input**

⇒ **Need reaction rates (S-factors, resonance strengths)**

Why do we spend so much effort on ^{19}Ne?

Novae observables

- Observation of line emission gamma-rays from stellar environments gives insight into nucleosynthesis process and conditions, eg ^{26}Al from various sites, ^{44}Ti from CCSN
- To date, no observation from novae but it is predicted.
- Timescale of ^{18}F decay is almost ideal for such observations – ejecta becomes transparent – and expected to dominate flux.
- Direct observation would provide firm constraints on modelling.
  - Isotopic rather than elemental information
  - Provides information hours not days after outburst
  - Illuminates explosion mechanism

Nucleus	τ	Emission	Nova type
^{13}N	862 s	511 keV	CO ONe
^{18}F	158 m	511 keV	CO ONe
^{7}Be	77d	478 keV	CO
^{22}Na	3.75 yr	1275 keV	ONe
^{26}Al	0.7×10^{6}yr	1809 keV	ONe

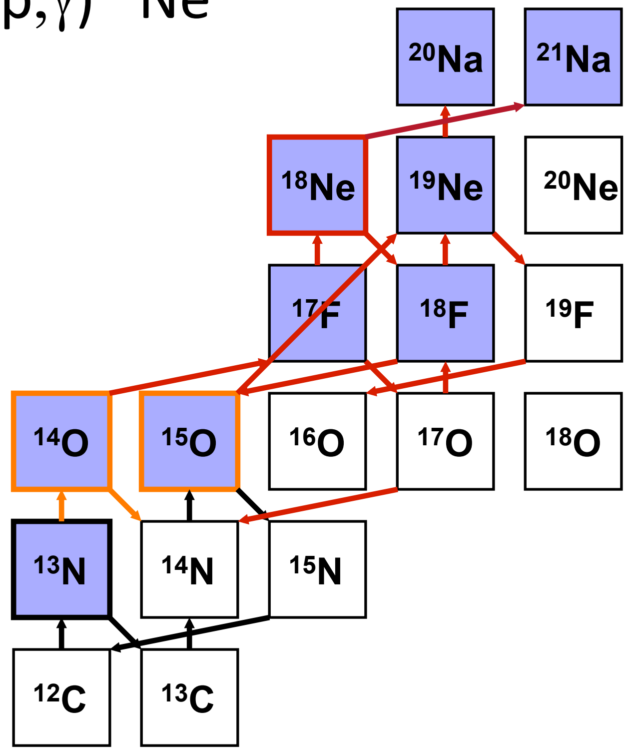
Artist's impression of INTEGRAL satellite

The ^{18}F abundance

- Final abundance of ^{18}F depends on rates of production/destruction processes
  - Production – decay of ^{18}Ne and $^{17}O(p,\gamma)^{18}F$
  - Destruction – $^{18}F(p,\alpha)^{15}O$ and $^{18}F(p,\gamma)^{19}Ne$

$^{18}F(p,\alpha)^{15}O$ dominates the destruction rate of ^{18}F

Only recently experimental data on $^{18}F(p,\gamma)^{19}Ne$ available



Both reactions proceed through resonances in ^{19}Ne

Why is it so hard?

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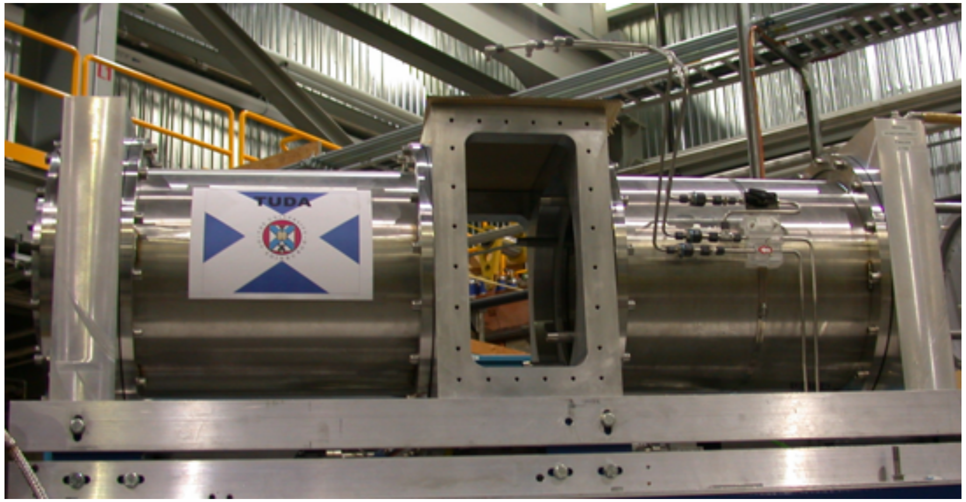
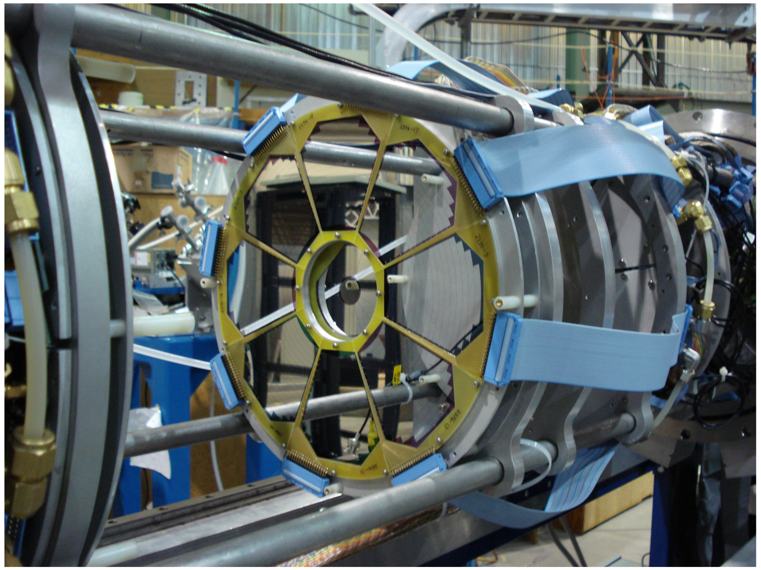
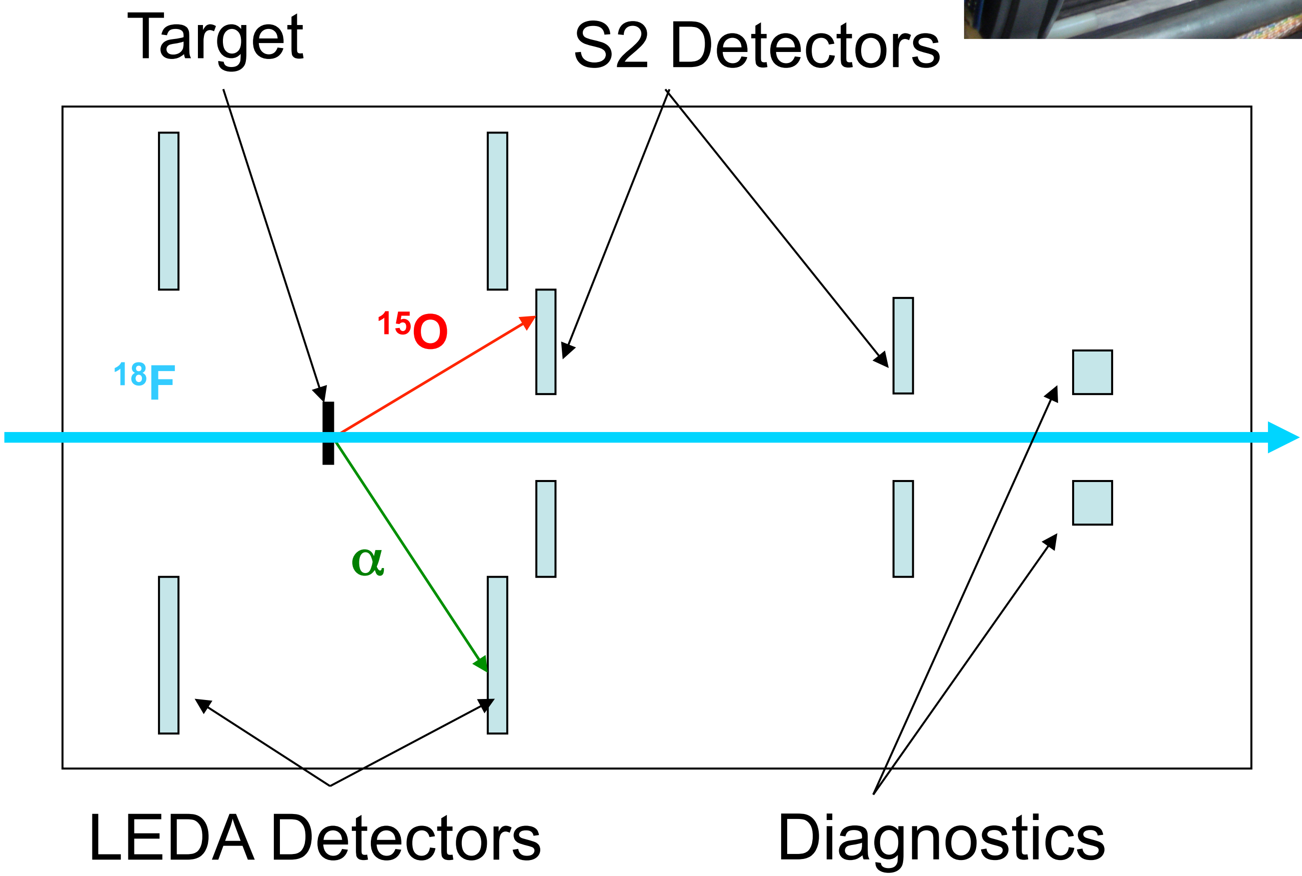


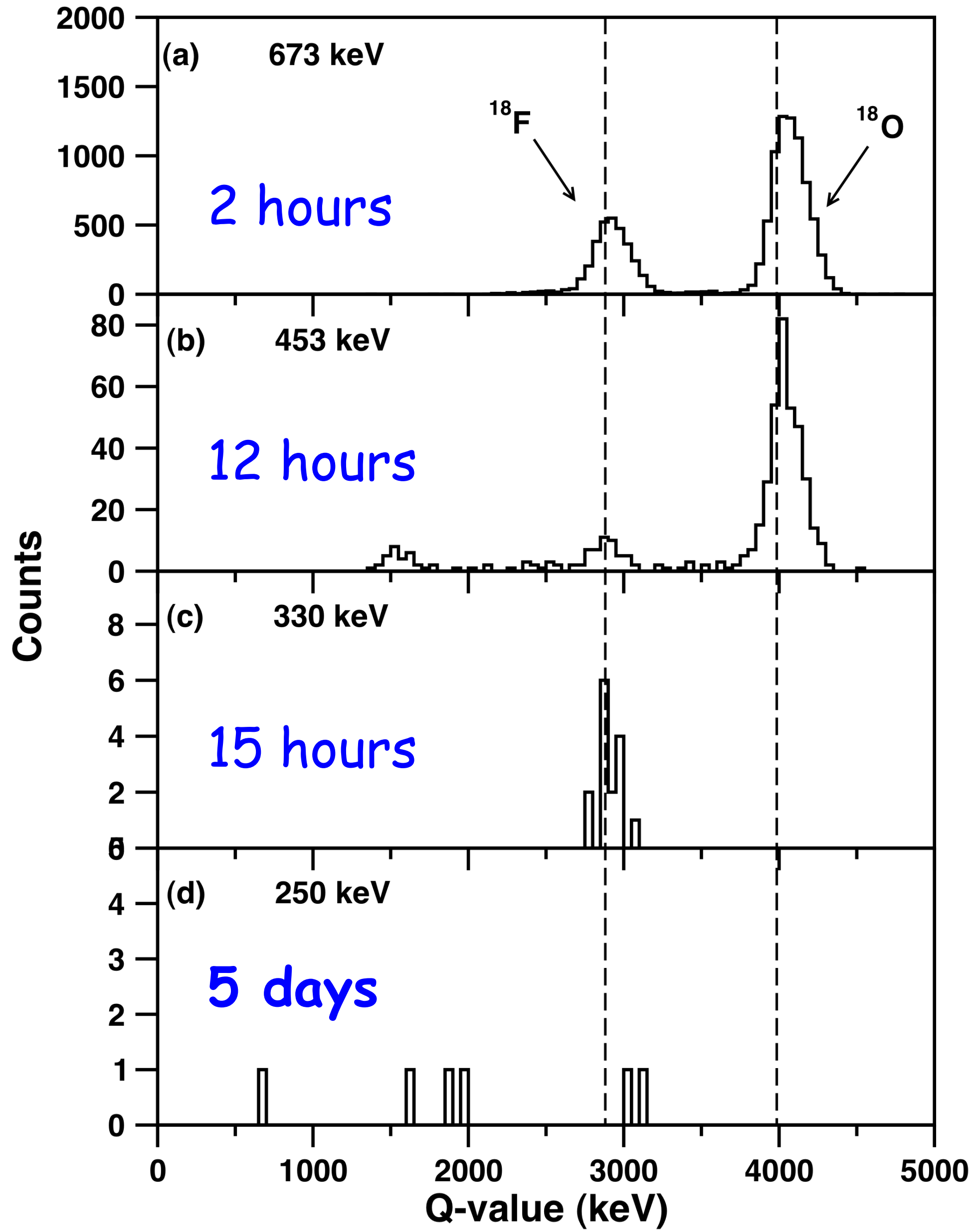




The $^{18}F(p,\alpha)^{15}O$ Data

Highest beam intensity available anywhere at required energy ~ 5e6 pps

Gamow window: ~ 50 – 350 keV



The ^{18}F(p,γ)^{19}Ne Data

Even worse!
2 events in 5 days at 665 keV.

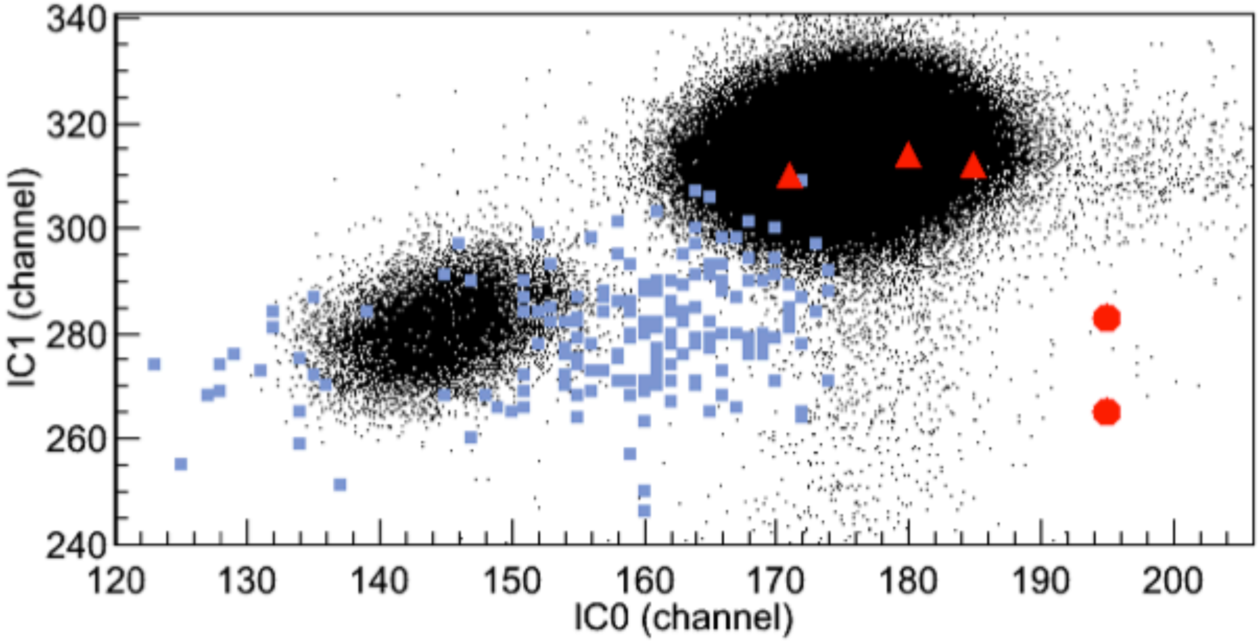


FIG. 1. Energy loss vs. energy loss plot obtained from the first two anodes in the IC. The attenuated beam run is shown in black and two well-separated loci are clearly visible signifying the presence of both ^{18}F and ^{18}O. Circles (triangles), both red online, correspond to observed ^{19}Ne (^{18}F) events when the separator was tuned to recoils. Squares (blue online) correspond to ^{19}F recoils during the separate ^{18}O beam run.

Why is it so hard?

Direct measurements extremely challenging.

Can we calculate rate using narrow resonance formula?

$$N_A\langle\sigma v\rangle = \frac{1.5399\times10^{11}}{\left(\frac{M_0 M_1}{M_0+M_1}T_9\right)^{3/2}}\sum_i(\omega\gamma)_i e^{-11.605\,E_i/T_9}$$

So need energies, spin/parities and partial widths

Previous level information (from Nesaraja et al. PRC 2007)

Proton threshold at 6.411 MeV.

Alpha threshold at 3.529 MeV.

=> Relevant states are unbound by around 3 MeV.

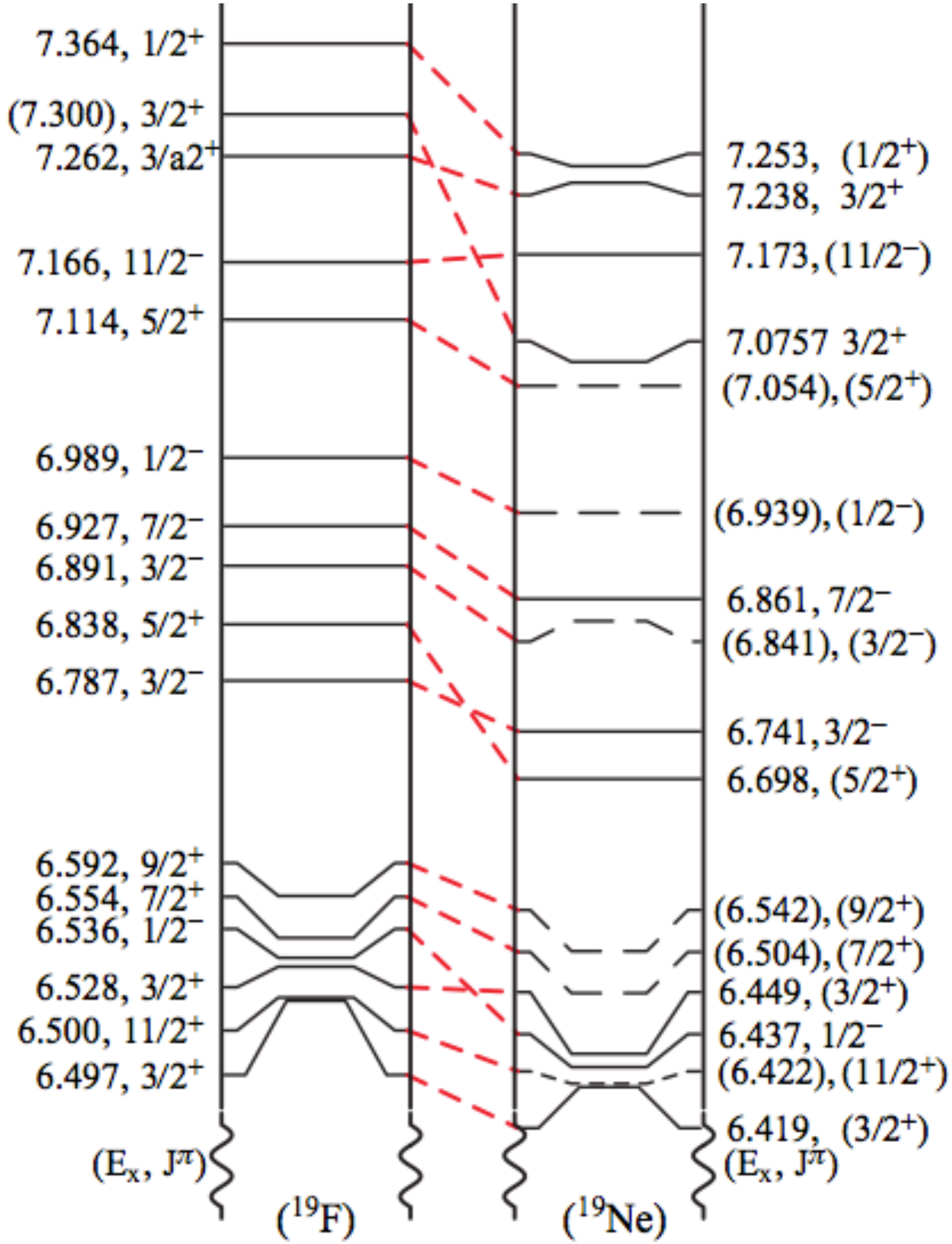
=> Cannot use gamma spectroscopy to get level information.

Level scheme poorly known.

^{19}Ne

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)
1	6.419	8(6)	$(\frac{3}{2}^+)$	0.77(41)	0.12(2)	2.2(4)E−37	0.27(27)
2	(6.422)	11(30)	$(\frac{11}{2}^+)$	0.35(18)	(0.1)	1.8(18)E−38	20(14)E−3
3	6.437	26(9)	$\frac{1}{2}^-$	[1(1)]	0.01	1.1(11)E−20	220(20) (M)
4	6.449	38(7)	$(\frac{3}{2}^+)$	1.1(6)	0.03(3)	4(4)E−15	1.3(10)
5	(6.504)	93(30)	$(\frac{7}{2}^+)$	0.14(8)	(0.1)	4.6(46)E−10	0.4(4)
6	(6.542)	131(30)	$(\frac{9}{2}^+)$	0.30(16)	(0.1)	2.7(27)E−12	1.3(11)E−2
7	6.698	287(6)	$(\frac{5}{2}^+)$	0.29(15)	0.01	1.2(12)E−5	1.2(10)
8	6.741	330(6)	$\frac{3}{2}^-$	5.0(26)	–	2.22(69)E−3	5.2(37)
9	(6.841)	430(30)	$(\frac{3}{2}^-)$	2.8(15)	(0.01)	9.7(97)E−3	25(18)
10	6.861	450(6)	$\frac{7}{2}^-$	2.3(12)	(0.01)	1.1(11)E−5	1.2(0.9)
11	(6.939)	528(30)	$(\frac{1}{2}^-)$	[1(1)]	(0.01)	3.4(34)E−2	99(69)
12	(7.054)	643(30)	$(\frac{5}{2}^+)$	[1(1)]	(0.1)	4.7(47)E−2	29(25)
13	7.0757	664.7(16)	$\frac{3}{2}^+$	[1(1)]	–	15.2(1)	23.8(12) (M)
14	7.173	762(5)	$(\frac{11}{2}^-)$	0.15(8)	(0.01)	9.8(98)E−8	1.2(10)E−2
15	7.238	827(6)	$\frac{3}{2}^+$	[1(1)]	–	0.35(35)	6.0(52)

Analogue assignments



Dashed black lines indicate predicted but not observed state – “missing states”.

Brackets indicate only tentative J^{π} assignments.

Why is it so hard?

Direct measurements extremely challenging.

Can we calculate rate using narrow resonance formula?

$$N_A\langle\sigma v\rangle = \frac{1.5399\times10^{11}}{\left(\frac{M_0M_1}{M_0+M_1}T_9\right)^{3/2}}\sum_i(\omega\gamma)_i e^{-11.605\,E_i/T_9}$$

So need energies, spin/parities and partial widths…

But only have some of this information ☹

And to make the calculations even more difficult…

The 665 keV resonance

Level at 7.07 MeV is broad, not narrow (49 keV)

Can't use narrow resonance formula.

State well above Gamow window, but tail of resonance extends across it.

Can interfere with other 3/2$^+$ states, including those below threshold.

How far does its influence extend?

^{19}Ne

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)
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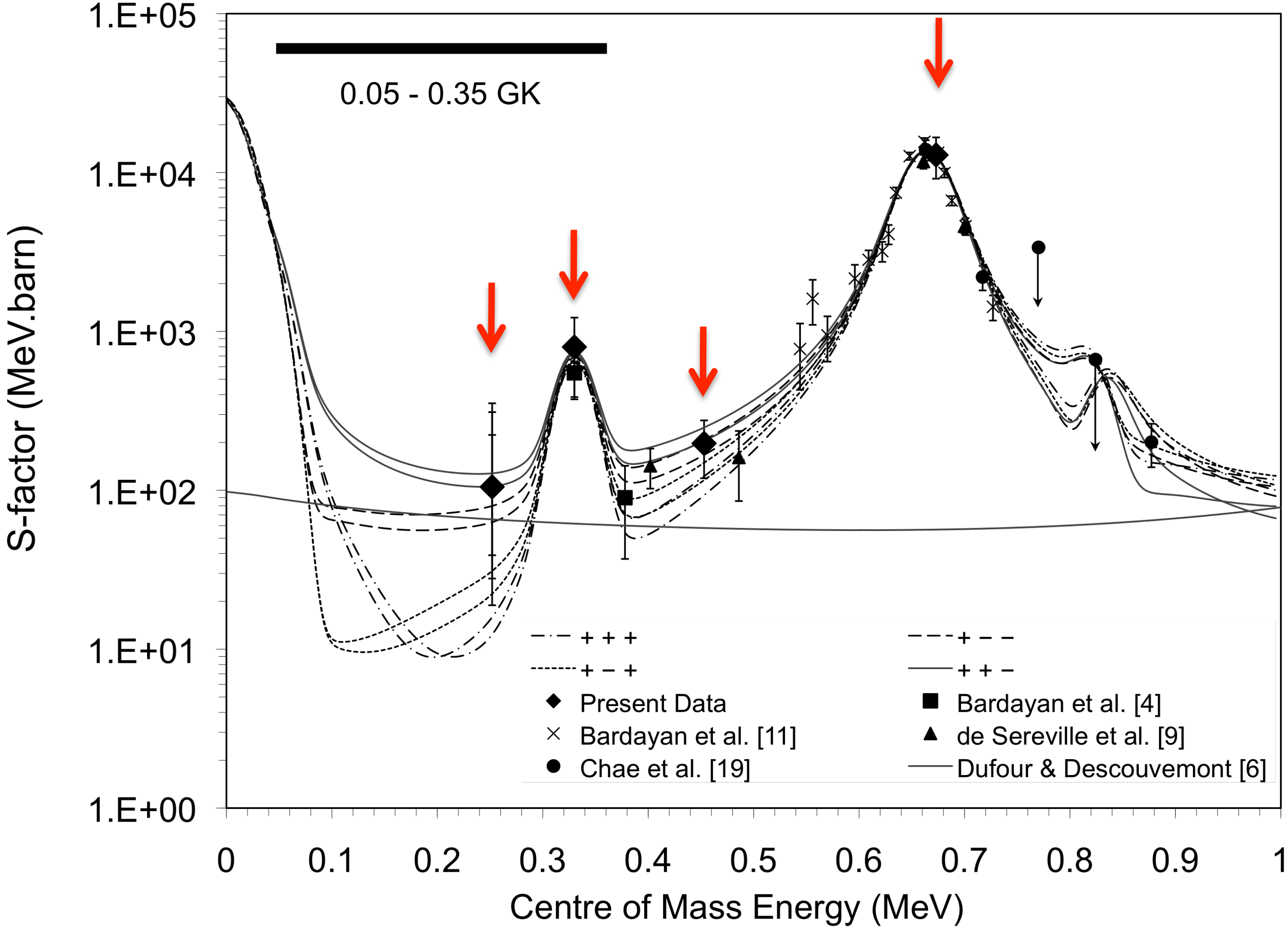
How can we use R-matrix to help?

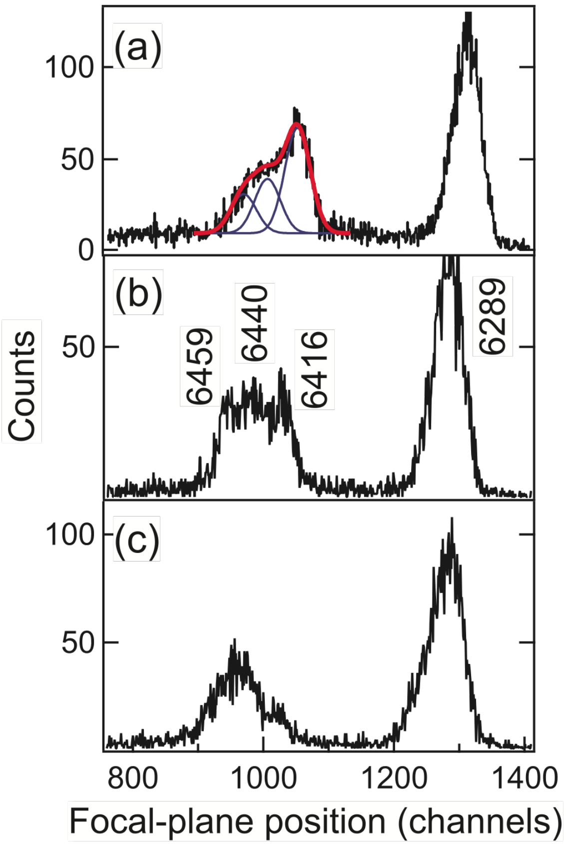
Using level information from Nesaraja et al. PRC 2007



- Interference between broad $3/2^+$ at 665 keV with $3/2^+$ states at 8 and 38 keV
- Large impact in Gamow window

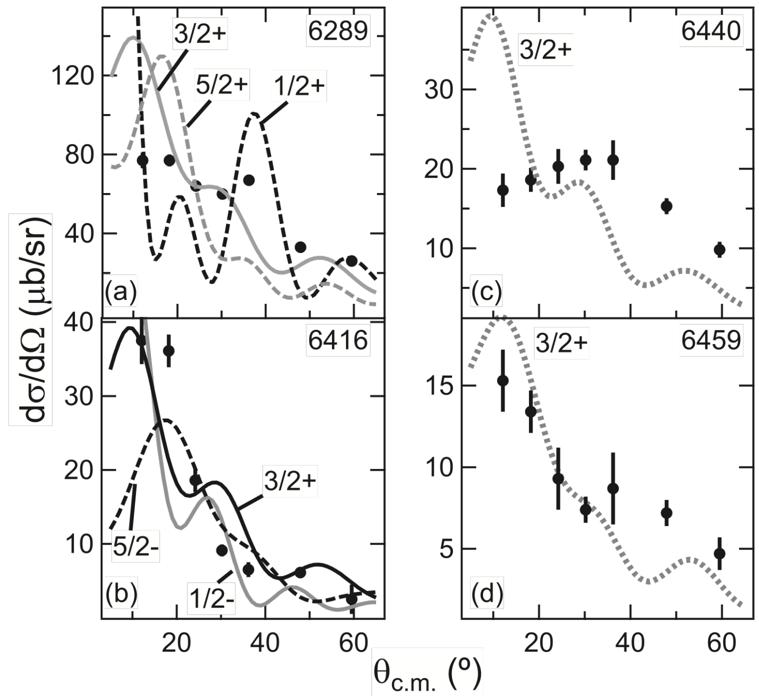
Beer et al., PRC(R) 83 042801 (2011)

Using new level information from $^{19}F(^{3}He,t)$



- Region close to proton-threshold can only be fitted with **three** narrow resonances, not two
- Angular distributions are all different

=> States cannot be 3/2^{+} pair, as assumed from mirror



⇒Where are the 3/2+ states? Could be below threshold.

⇒ 5 keV plays no role (unless 3/2+)

⇒ 48 keV could be important depending on J^{π} and proton width.

Laird et al. Phys. Rev. Lett. 110, 032502 (2013)

TABLE I. Resonance parameters from the present work compared to previous values. One should consider an additional systematic uncertainty of ±2 keV in E_x from the present work (see text).

Present work					Previous work[a]		
E_x (MeV)	E_{cm} (keV)	J^{π}	Γ_p (keV)[b]	Γ_α (keV)[b]	E_x (MeV)	E_{cm} (keV)	J^{π}
6.014(2)	−397	$3/2^-$	⋯	⋯	6.016	−395	$(1/2, 3/2)^-$
6.072(2)	−339[c]	$(3/2^+, 5/2^-)$	0.143	6×10^{-4}	6.078	−333	⋯
6.097(3)	−314	$(7/2, 9/2)^+$	⋯	⋯	6.107	−304	⋯
6.132(3)	−282[c]	$(3/2^+, 5/2^-)$	0.143	7×10^{-4}	6.138	−276	⋯
6.289(3)	−122	⋯	⋯	⋯	6.290	−121	$(1/2, 3/2, 5/2)^+$
6.416(3)	5[c]	$(3/2^-, 5/2^+)$	4.7×10^{-50}, 1.2×10^{-51}	0.5, 0.126	6.419(6)	8	$(1/2, 3/2)^-$
6.440(3)	29	$(11/2^+)$	⋯	⋯	⋯	⋯	⋯
6.459(3)	48[c]	$(5/2^-)$	8.4×10^{-14}	5.5	6.449(7)	38	$(3/2^+)$
6.700(3)	289	⋯			6.698(6)	287	$(5/2^+)$
6.742(2)	331[c]	$(3/2^-)$	2.22×10^{-3}[d]	5.2[d]	6.741(6)	330	$(3/2^-)$
6.862(2)	451	$(7/2^-)$	1.1×10^{-5}[d]	1.2[d]	6.861(6)	450	$(7/2^-)$

Key result – previously assumed $3/2^+$ pair at 8 and 38 keV are now 5, 29 and 48 keV. More importantly, all J^{π} are different so **cannot be $3/2^+$ pair.**

Remaining questions:

- what is J^{π} of 48 keV state (could make significant contribution)?
- are there any $3/2^+$ states? (if not, interference with 665 keV not important)

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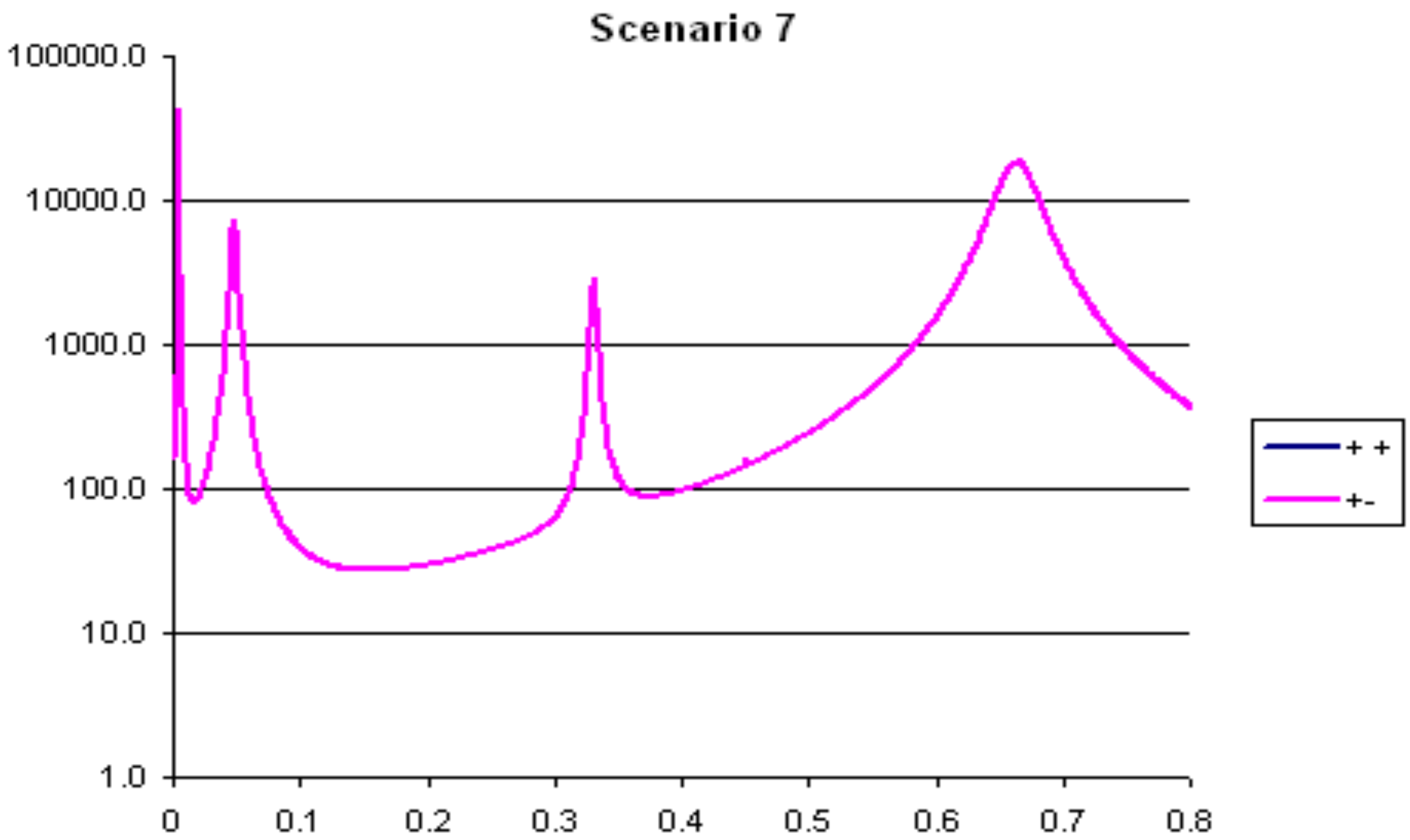
How can we use R-matrix to help?

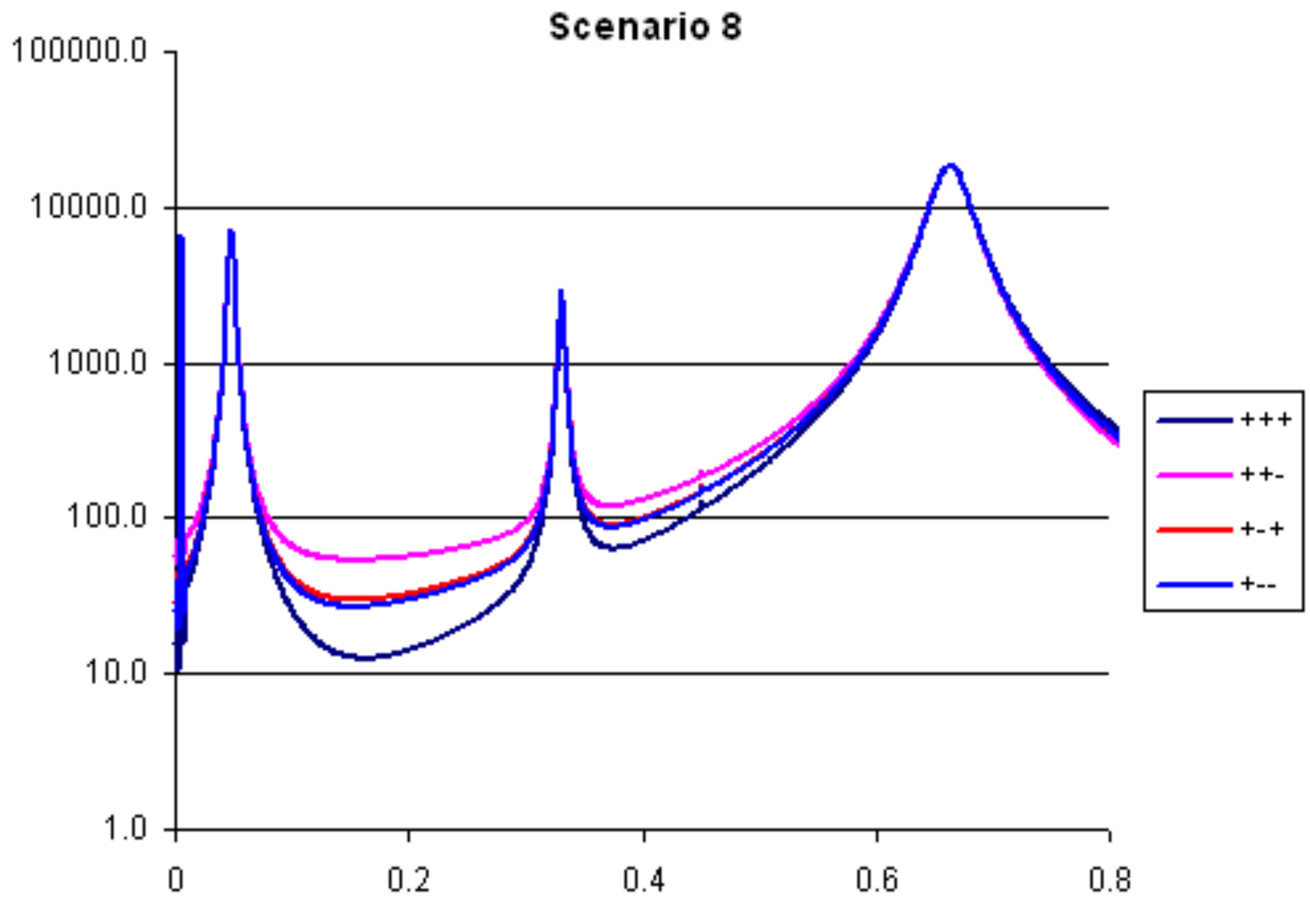
1. Constraints on reaction rate.

Including 3/2- interference



5 keV	3/2-	4.7e-53 MeV	5e-4 MeV
48 keV	5/2-	8.4e-17 MeV	5.5e-3 MeV
331 keV	3/2-	2.22e-6 MeV	5.2e-3 MeV
451 keV	7/2-	1.1e-8 MeV	1.2e-3 MeV
665 keV	3/2+	0.015 MeV	0.024 MeV

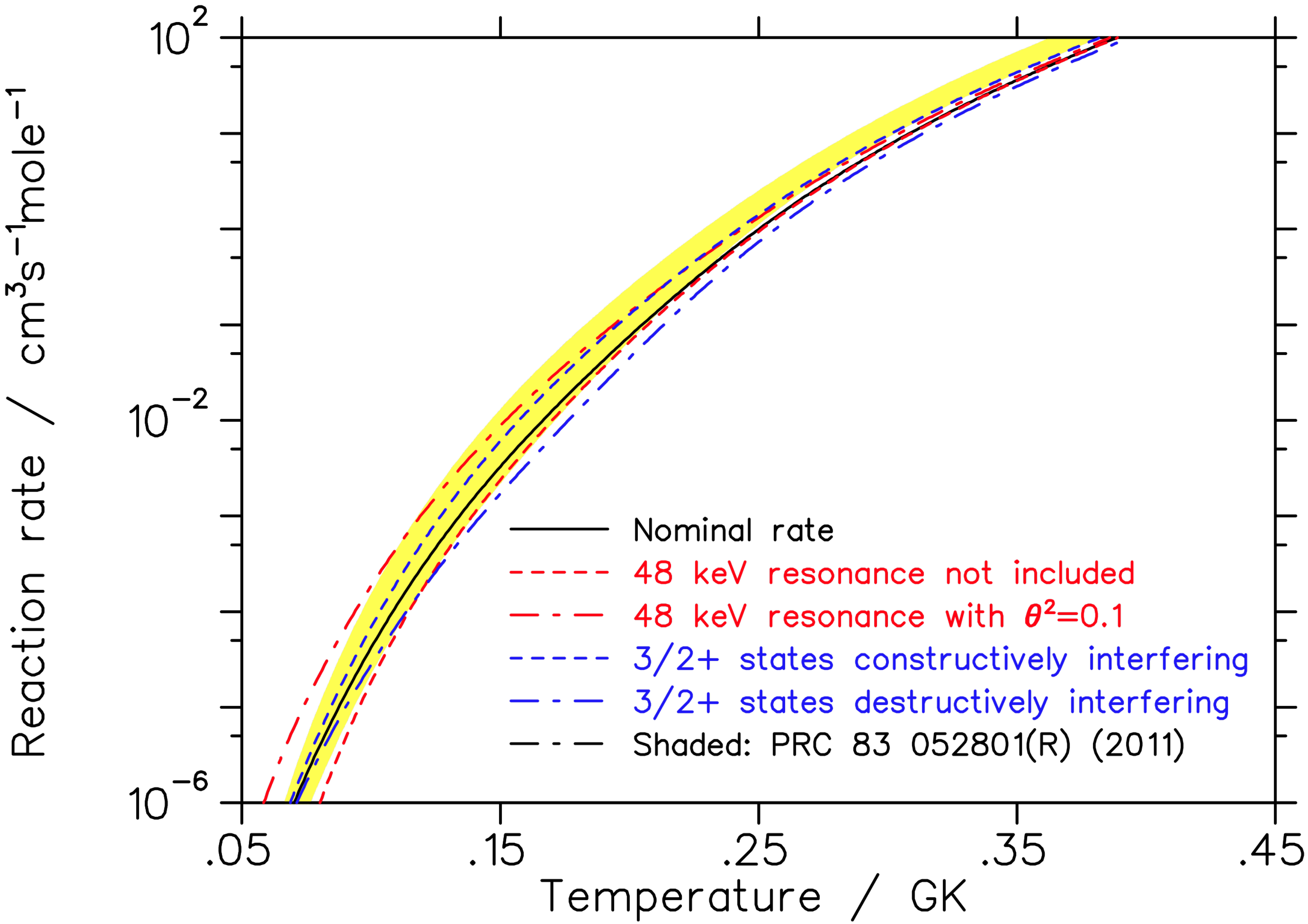
Including 3/2+ sub-threshold states



-0.339	3/2+	gp=-0.143	Ga=6e-4 MeV
-0.279	3/2+	gp=-0.143	Ga=7e-4 MeV
5 keV	5/2+	1.2e-54 MeV	1.26e-4 MeV
48 keV	5/2-	8.4e-17 MeV	5.5e-3 MeV
331 keV	3/2-	2.22e-6 MeV	5.2e-3 MeV
451 keV	7/2-	1.1e-8 MeV	1.2e-3 MeV
665 keV	3/2+	0.015 MeV	0.024 MeV

How can we use R-matrix to help?

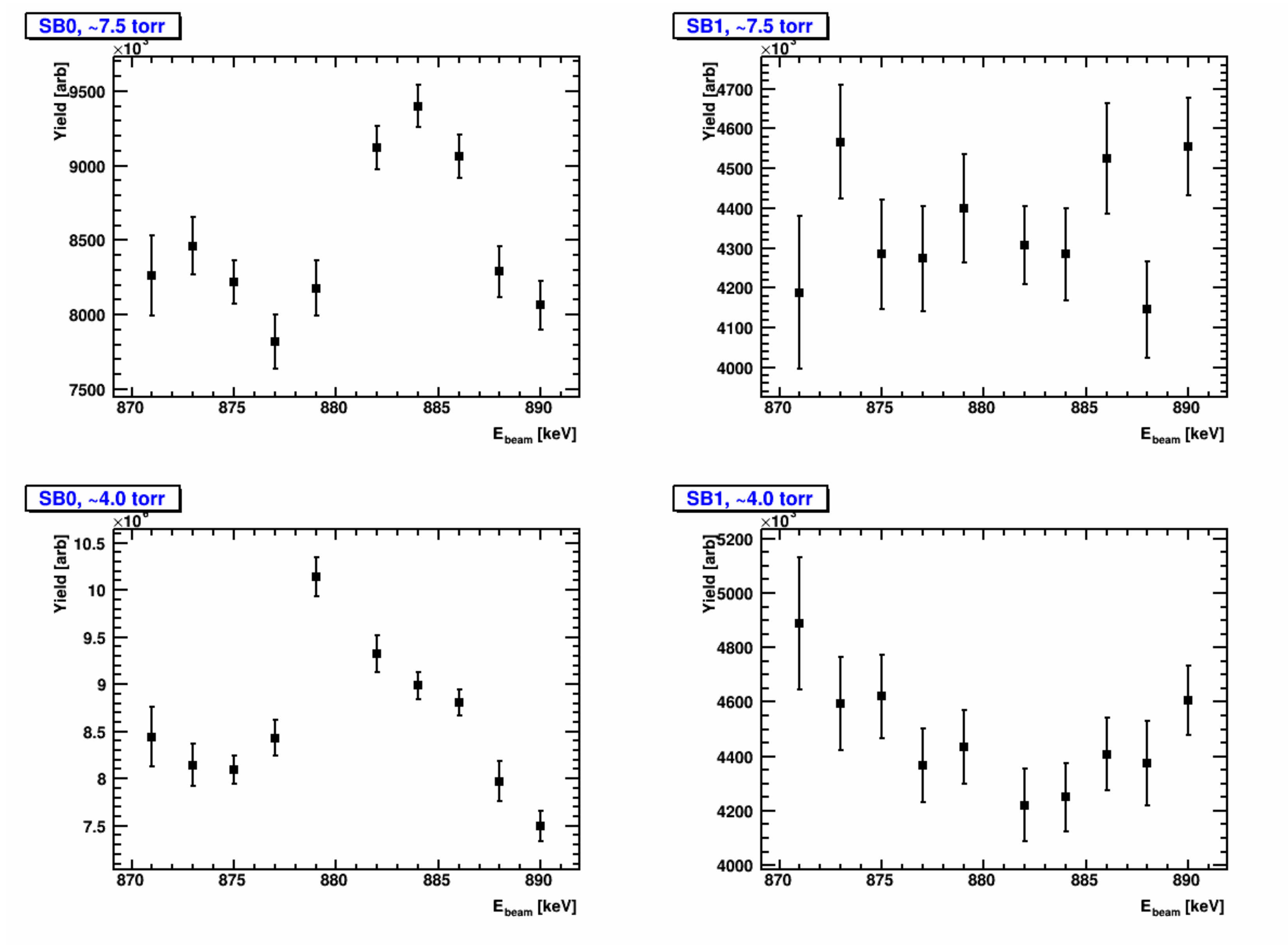
1. Constraints on reaction rate.
2. Identify measurements needed



Largest uncertainty (factor 2) from unknown widths of 48 keV.
Interference of 3/2+ states gives 50% uncertainty.
Parameters of 5 keV not influential.

Using other channels to get information

$^{15}N(\alpha,\alpha)$ data as test for $^{15}O(\alpha,\alpha)$



Future programme

Planned measurements –

- $^{15}O(\alpha,\gamma)^{19}Ne$ – 330 keV - Γ_{γ}
- $^{15}O(\alpha,\alpha)^{19}Ne$ – 330 keV – Γ_{α} (Γ_{T})
- $^{19}F(^{3}He,t)^{19}Ne$ – high resolution of near threshold states compared to 665 keV
- $^{19}F(^{3}He,t)^{19}Ne$ – lower resolution scan over many states.

Thank you for your attention

The DRAGON collaboration

The TUDA collaboration

+ A. Parikh, R. Longland, J. Jose (UPC Barcelona)

A. Chen (McMaster Uni)

C. Deibel (LSU)

K. Wimmer (MSU)

T. Faestermann, H.F Wirth (MLL)

TRIUMF