Recent results on stellar and explosive nucleosynthesis

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Coverage

^{18}F production in novae - can we detect the gamma ray emission?

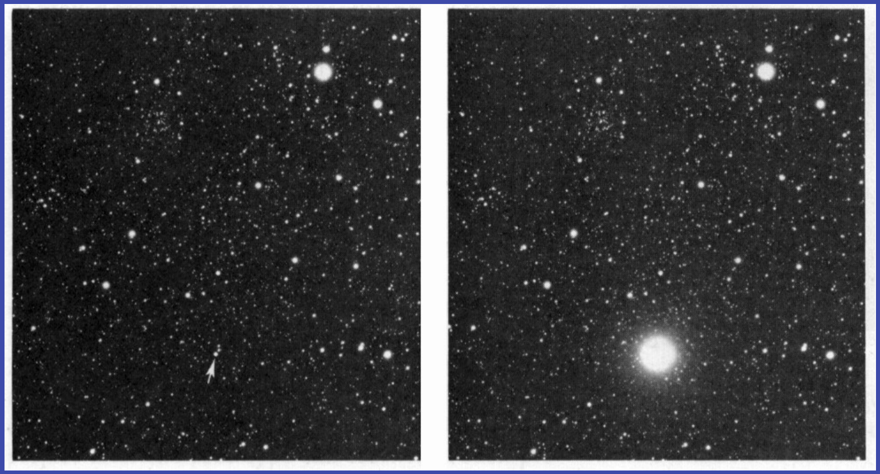
s-process in massive stars - is oxygen a poison?

$^{3}He+^{4}He$ rate – a key for solar neutrinos and the BB Li problem

NOVAE

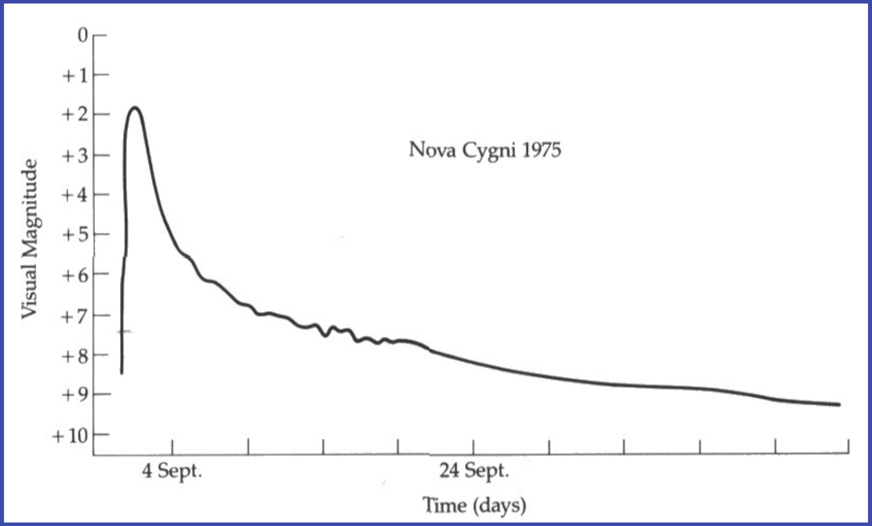
Humans have been seeing novae ("new stars") in the sky for hundreds of thousands of years

(20-60 per year in Milky Way)

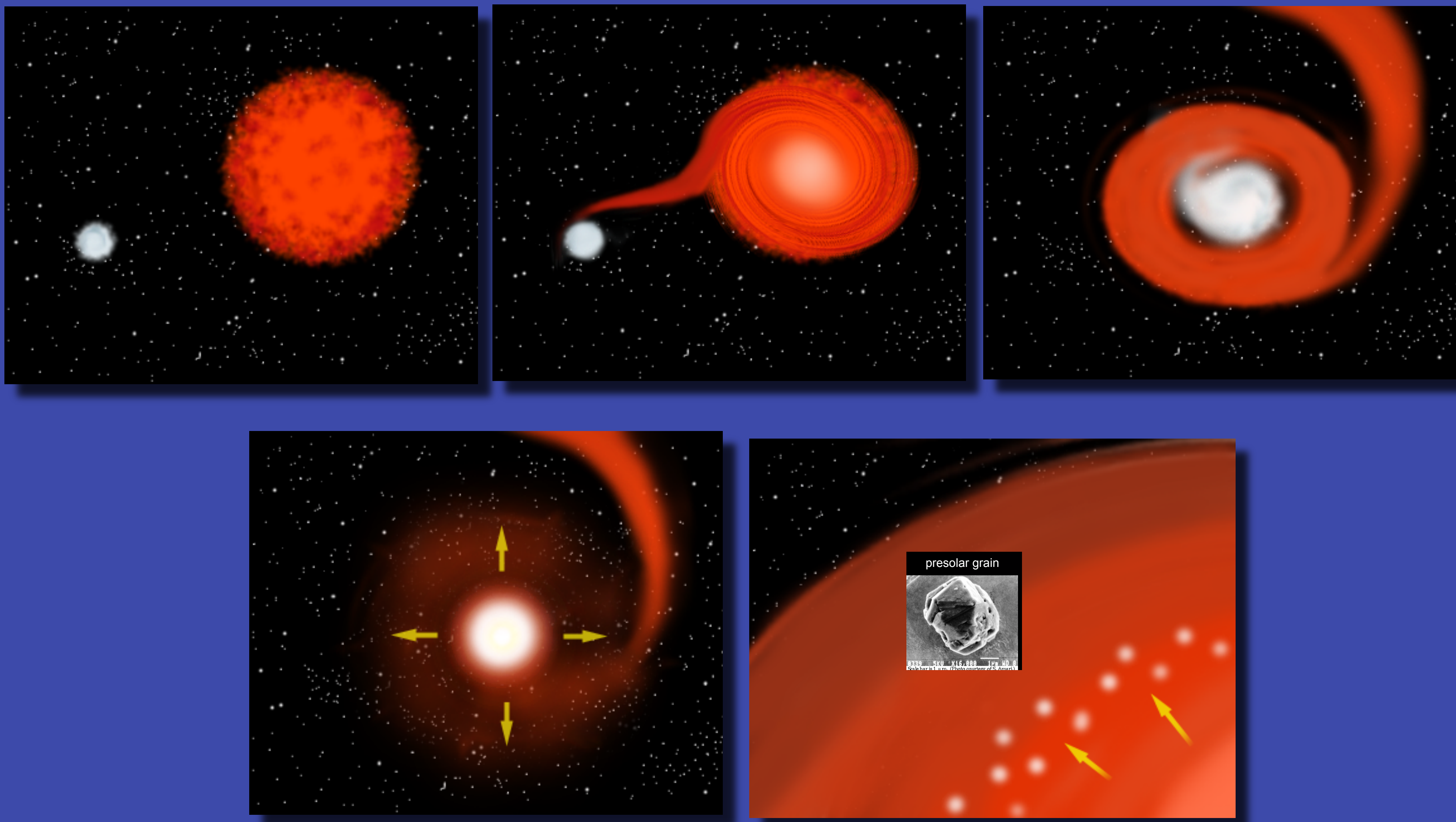


From light curve we can estimate the peak temperature ($3x10^8$K) and duration (hours) of the outburt

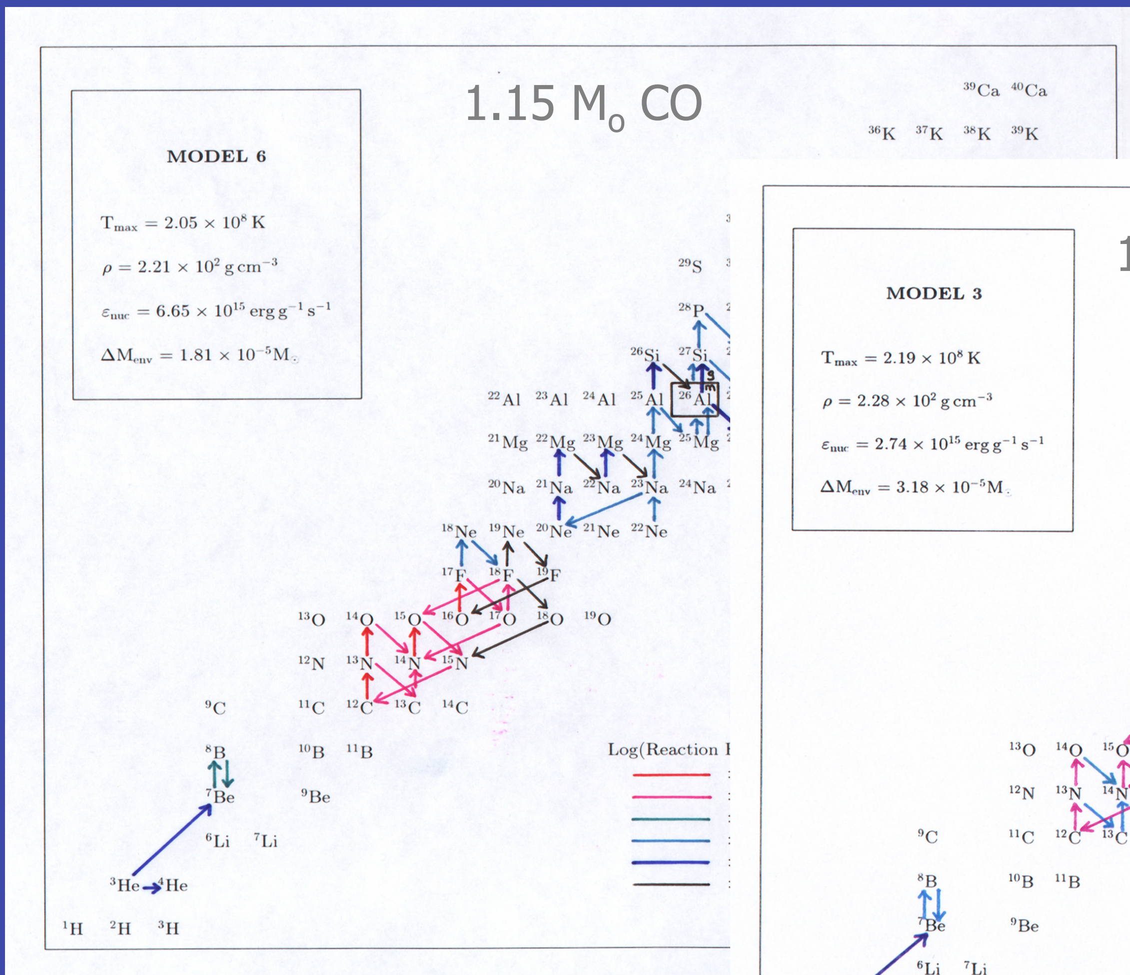
We can also determine the element abundance from spectroscopic measurements

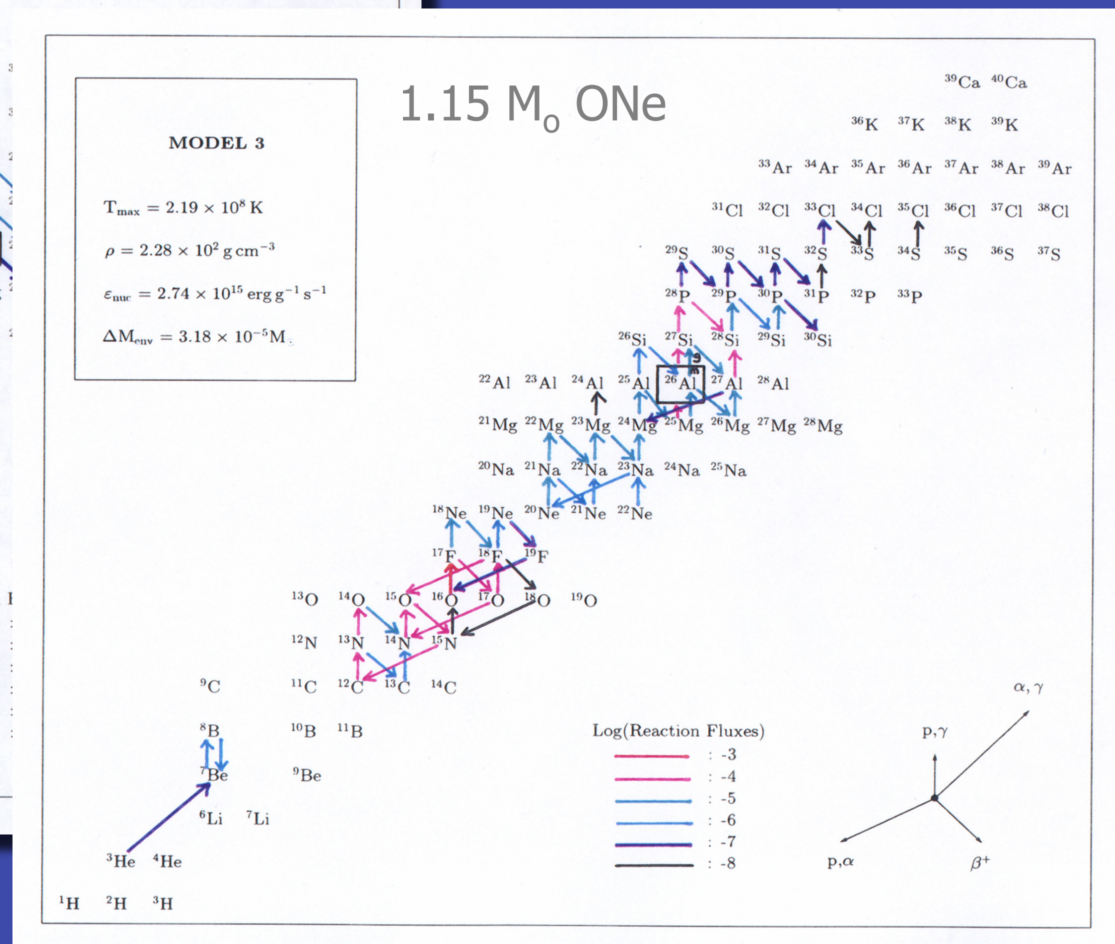


The outburst arises from explosive burning on compact companion of a close binary system

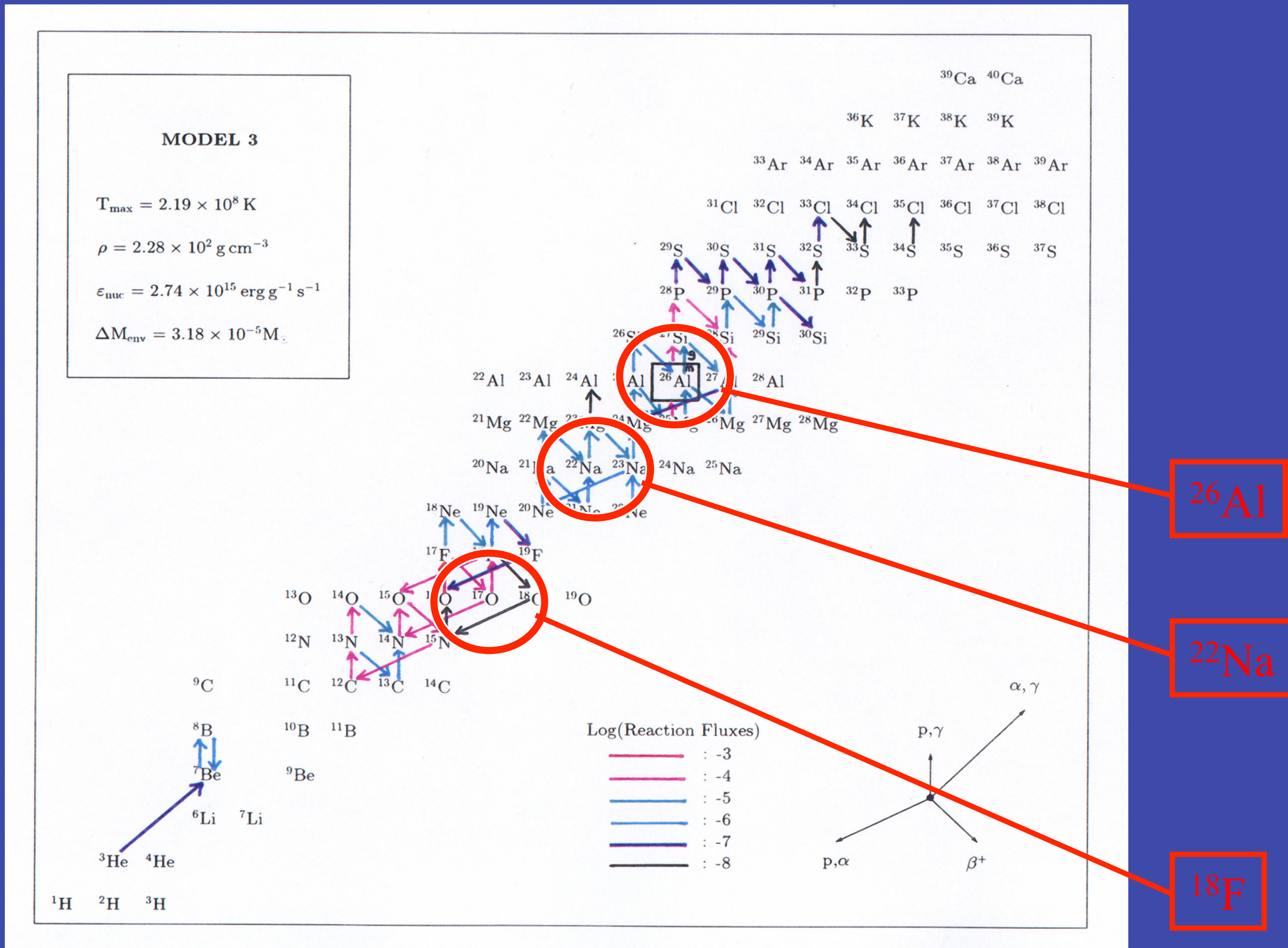


In this hot, dense environment the nuclear reactions occurring are very different from those inside a star and involve cycles of reactions up to sulphur



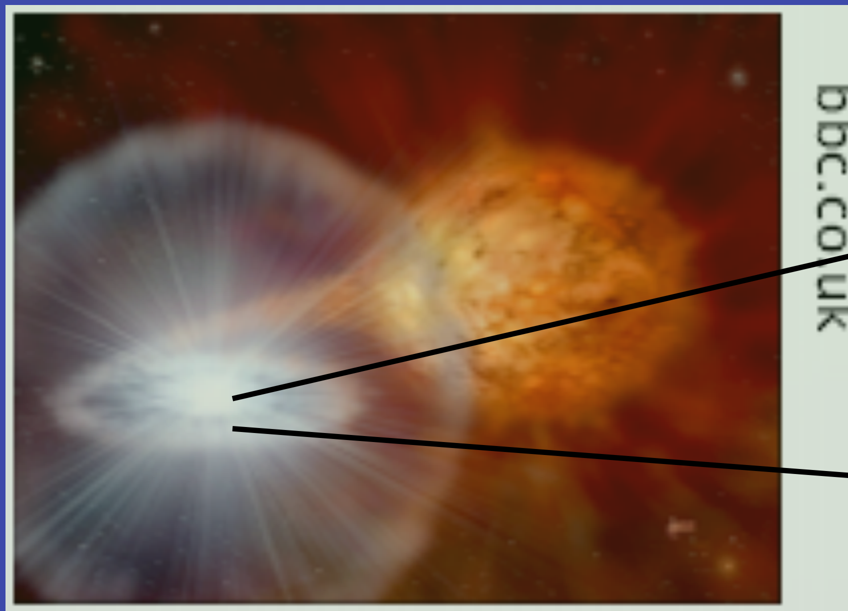


Note that many of these reactions involve unstable nuclei and some of these are relatively long lived and so will remain after the nova outburst dies away



If we could identify gammas emitted from these decays we would have a strong check on models

To detect gammas we need to be above the atmosphere



511keV gammas following β-decay of ^{18}F is one of the most promising observables as the halflife of 158 minutes matches timescale for ejecta to become transparent.
(Note this is days/weeks before the rise of the optical luminosity)

Original estimates of ^{18}F production implies satellites could observe out to 2-3 pc
…… however, no gamma signal has yet been identified
…… and the models fail to reproduce the amount of material ejected as identified from optical and radio observations

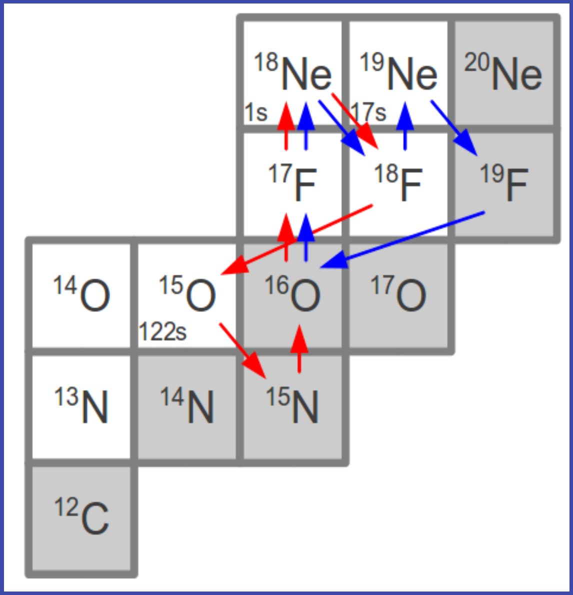
The relevant nuclear reaction input to models

To predict the amount of ^{18}F produced in models we need the rates of the reactions which produce it and also those of the reactions that destroy it.

Production: ^{17}O(p,γ) ^{18}F and beta decay of ^{18}Ne
Destruction ^{18}F(p,α)^{15}O and ^{18}F(p,γ) ^{19}F

Both destruction reactions can lead to the material being recycled round to ^{18}F again.

However the (p,α) (red arrows) is much slower than the (p,γ) (blue arrows) because of the delay in the relatively long lived ^{15}O.



Sensitivity studies reveal that uncertainties in the (p,α) and (p,γ) rates are the limiting factor in our modeling of novae

As the temperature increases during the outburst, the nuclei collide with higher energies. Hence the models require the reaction rate (cross section) to be measured over a range of energies

We have the three classic problems with nuclear astrophysics measurements:

- need a radioactive beam with resulting low intensities
- reaction rates are small because of the low energies
- large backgrounds from radiation from the beam

As a consequence no (p,α) or (p,γ) measurements exist that extend into the energy region relevant for novae

As no measurements of rates exist, the models have been run with rates calculated based on capture through resonant states in the compound nucleus.

$$N_A < \sigma v >= 1.54 \cdot 10^{11} (\mu T_9)^{-3/2} (\omega\gamma)[\mathrm{MeV}] e^{\frac{-11.605\,\mathrm{E}_p[\mathrm{MeV}]}{\mathrm{T}_9}} \frac{\mathrm{cm}^3}{\mathrm{s\ mole}}$$

$$\omega\gamma = \frac{2J_R + 1}{(2j_t + 1)(2j_p + 1)} \frac{\Gamma_p \Gamma_\gamma}{\Gamma_p + \Gamma_\gamma}$$

$$\text{for } \Gamma_p << \Gamma_\gamma :$$

$$\omega\gamma = \omega\Gamma_p$$

So we need the energies, spins and partial widths of the relevant excited states in ^{19}Ne

PROBLEM

The spectroscopy of ^{19}Ne is not well known and those states that have been located don't always have spins or partial decay widths measured.

First problem…

There are many states and most level data is tentative!

Nesaraja PRC 75 (2007) 055809

The capture will preferentially go by low angular momentum transfer (lower centrifugal barrier)

So key states will be:

l=0 at 8, 38, 665 keV

l=1 at 26, 330

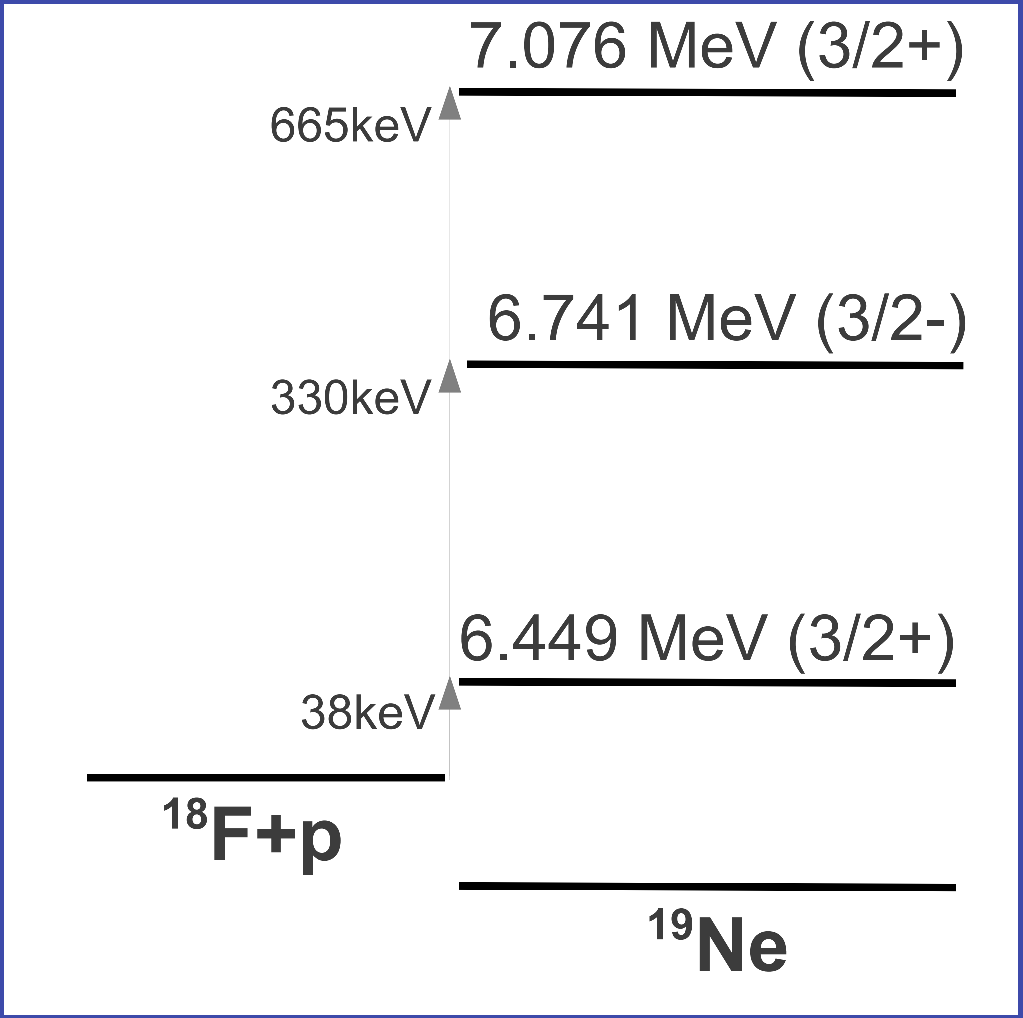
E_R (keV)	J^π
8	3/2+
11	11/2+
26	1/2-
38	3/2+
93	7/2+
131	9/2+
287	5/2+
330	3/2-
430	3/2-
450	7/2-
528	1/2-
643	5/2+
665	3/2+
762	11/2-
827	3/2+
842	1/2+
1009	7/2+
1089	5/2+
1120	5/2-
1147	5/2-
1197	3/2+
1233	1/2-
1289	5/2-
1408	7/2+
1415	11/2+
1533	5/2+
1603	5/2+
1658	1/2+

Main low spin states thought to dominate capture rate

665 keV
$\Gamma\alpha$ from (p,α)
No $\Gamma\gamma$ and no ^{19}F analogue assigned
so Nesaraja assumed $\Gamma\gamma$ = 1eV
based on average of nearby states

330 keV
$\Gamma\alpha$ from (p,α)
$\Gamma\gamma$ = 5+/-3 eV from association with ^{19}F
analogue at 6.787MeV

38 keV
Both $\Gamma\alpha$ and $\Gamma\gamma$ from association with
^{19}F analogue at 6.528MeV

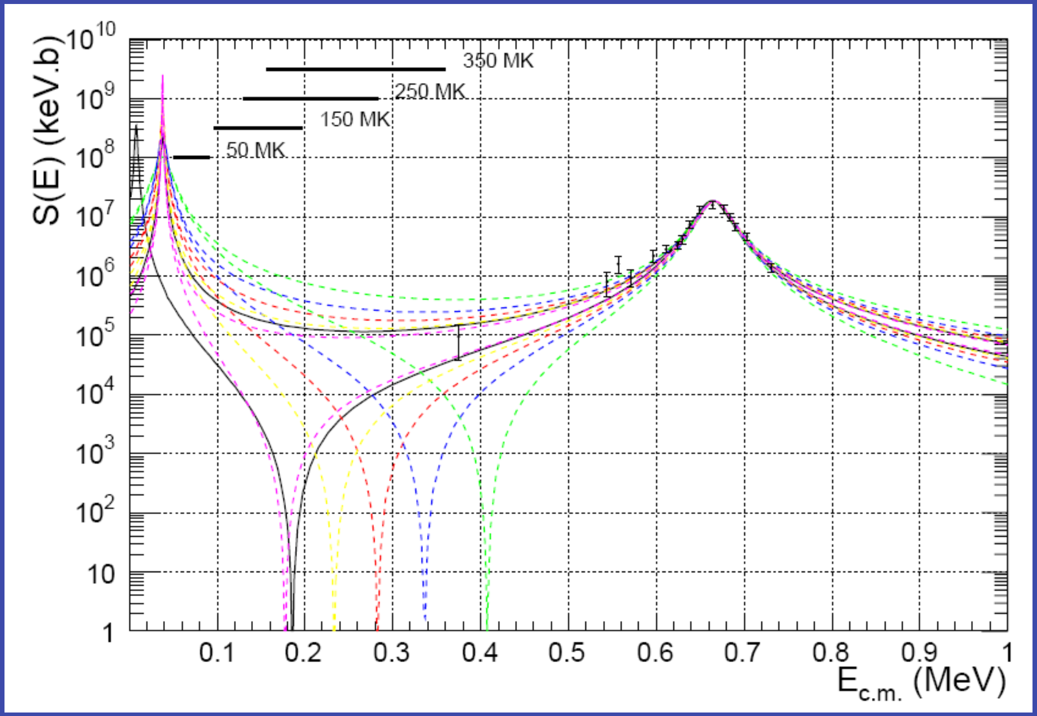


2nd Problem…

States of the same spin-parity interfere

Signs of interference terms are unknown

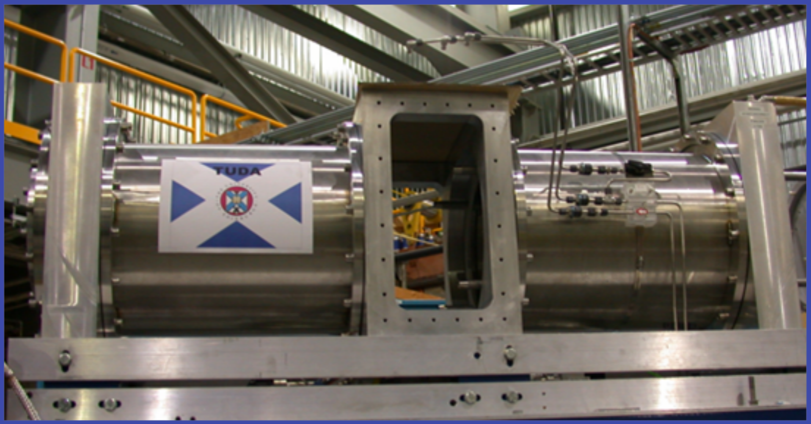
N. de Sereville NPA 758 (2005) 745c

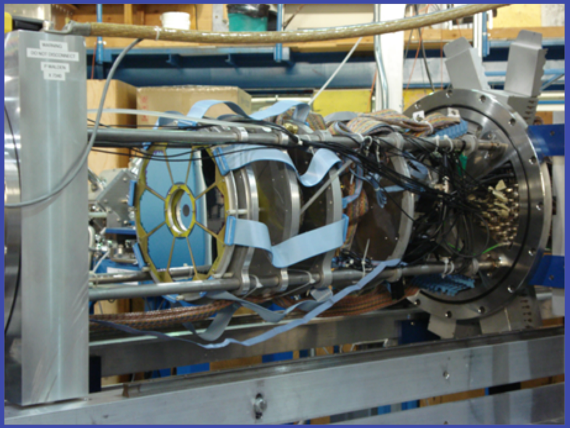


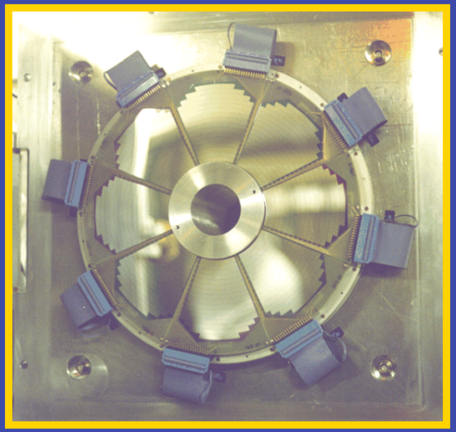
Caution: It is not possible to calculate the reaction yield even if you know the energies, spins, parities and partial widths of all the states – there is a phase!

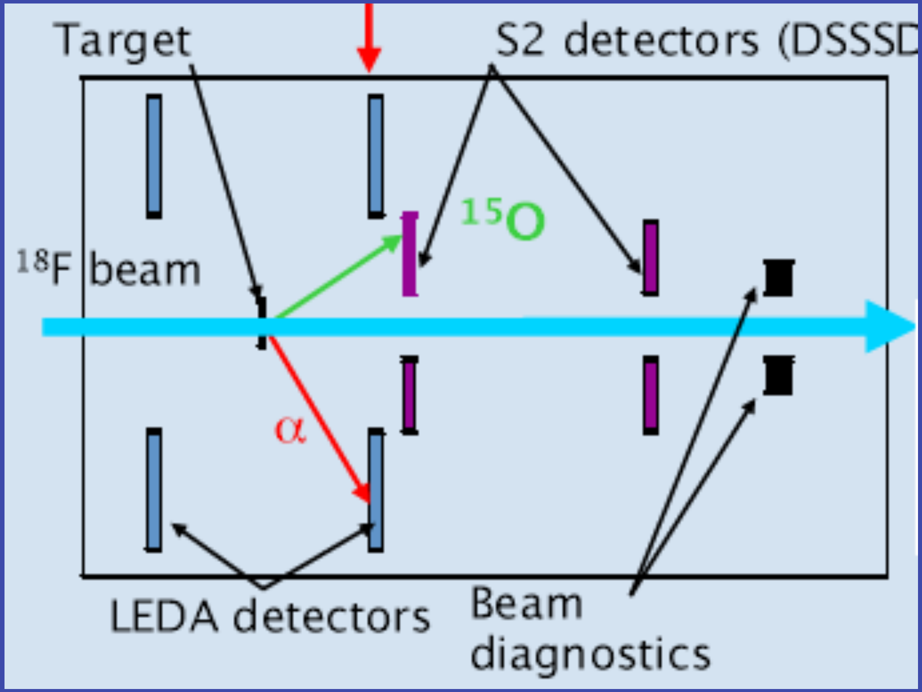
HAVE TO GO AND MAKE THE MEASUREMENT

Direct measurement of (p,α) rate using ^{18}F beam at TRIUMF on H target



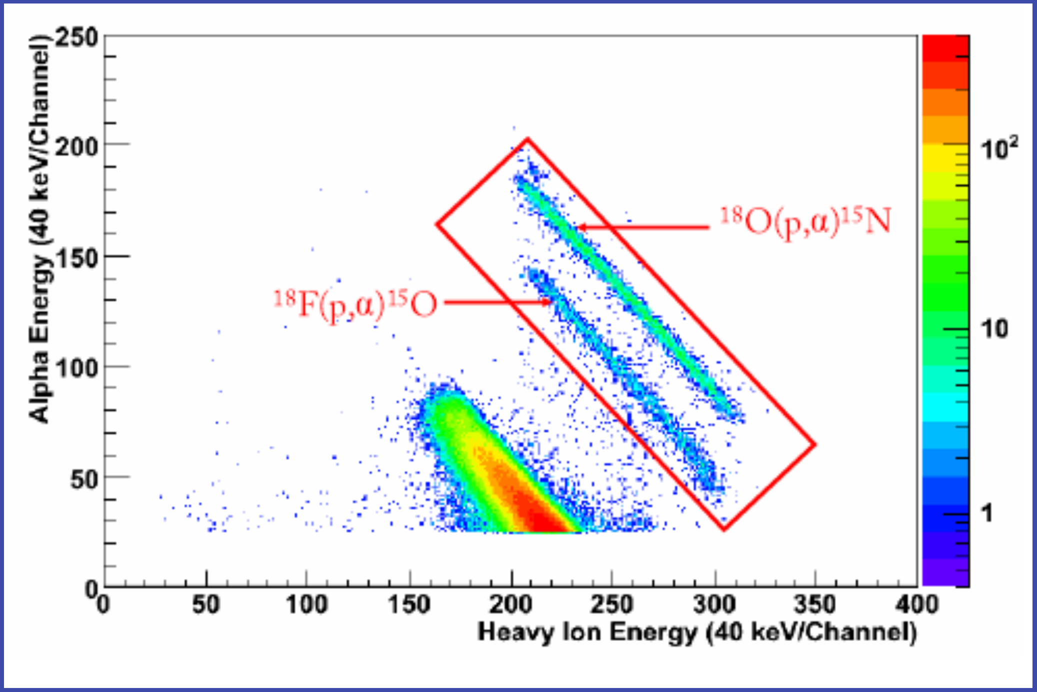






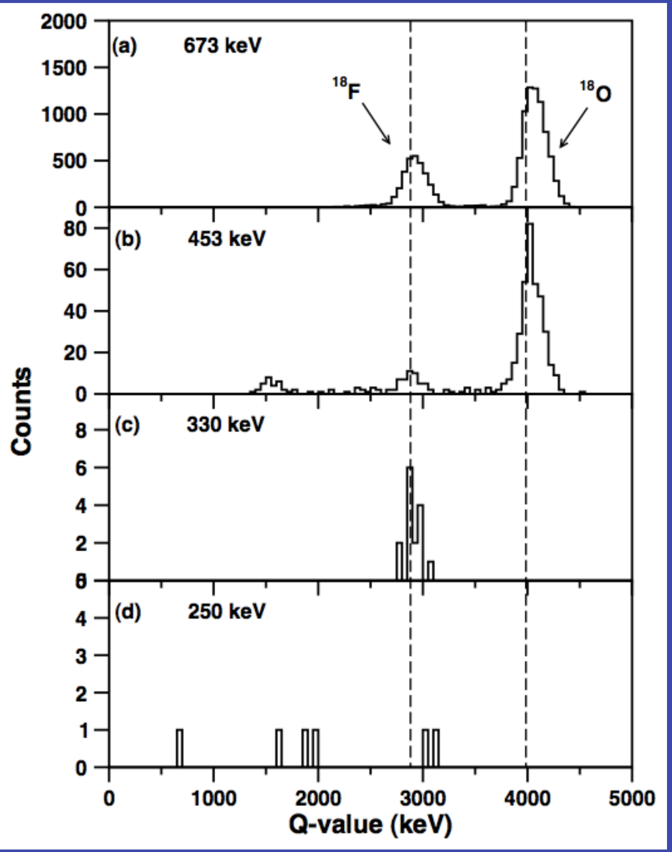
TUDA Array

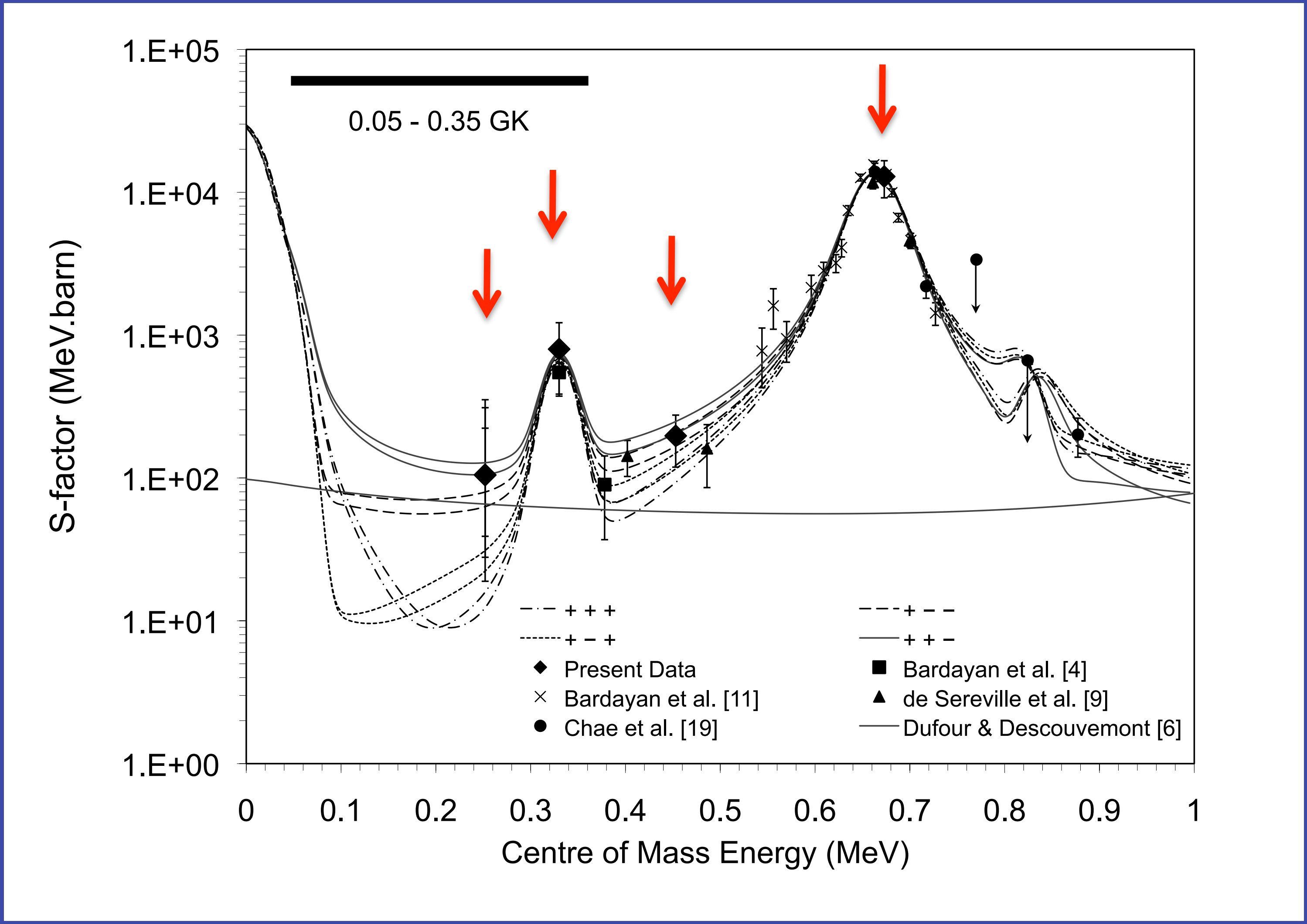
Array of segmented annular silicon detectors



E_{beam} = 12.96 MeV
Kinematic coincidence allows rejection of ^{18}O contaminant beam

E_{α} for four beam energies

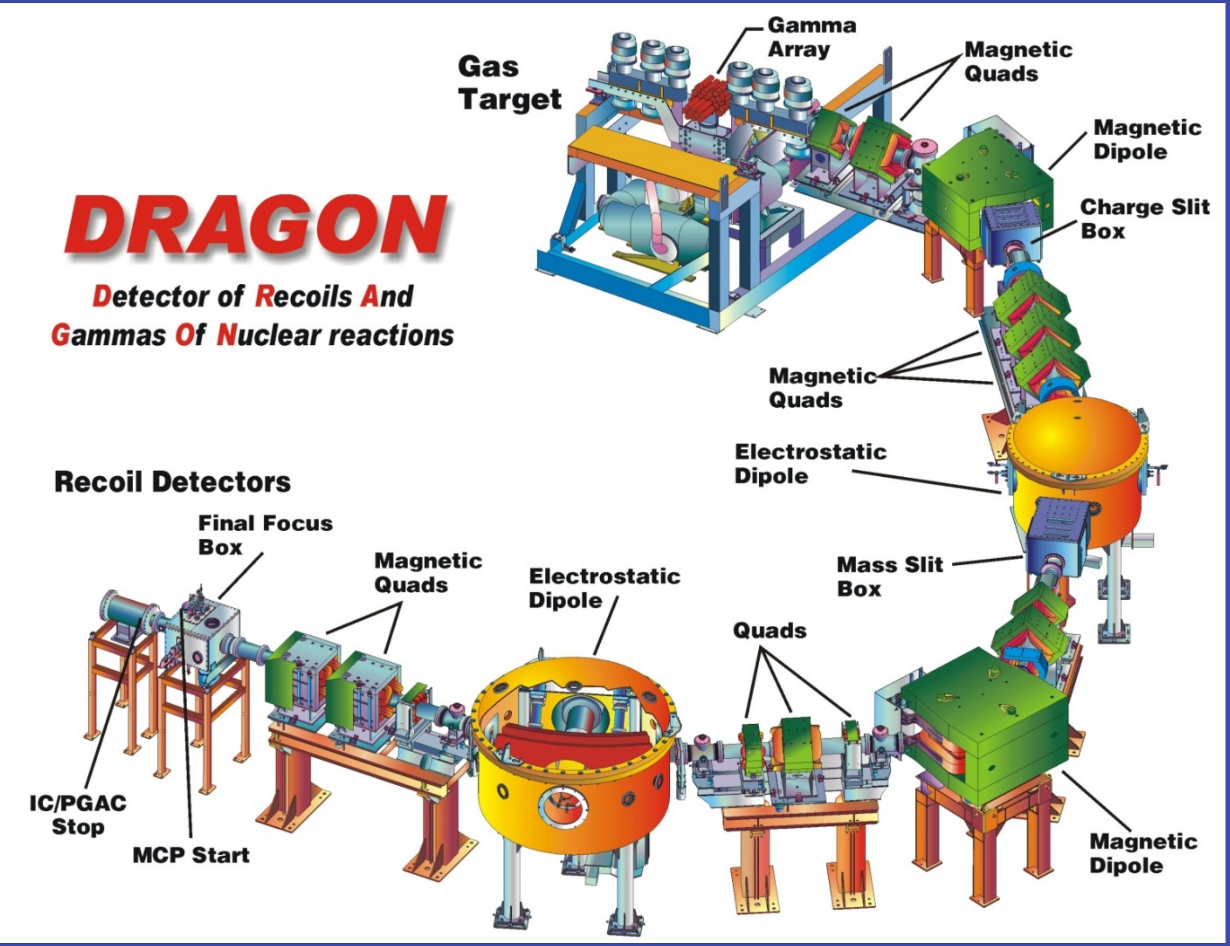




C E Beer et al. PRC 83 042801(R) 2011

Managed first measurement into nova region, but further progress awaits major increase in beam intensity – but while waiting, could we pin down the relative phases by more accurate measurements in the region above the 330 keV?

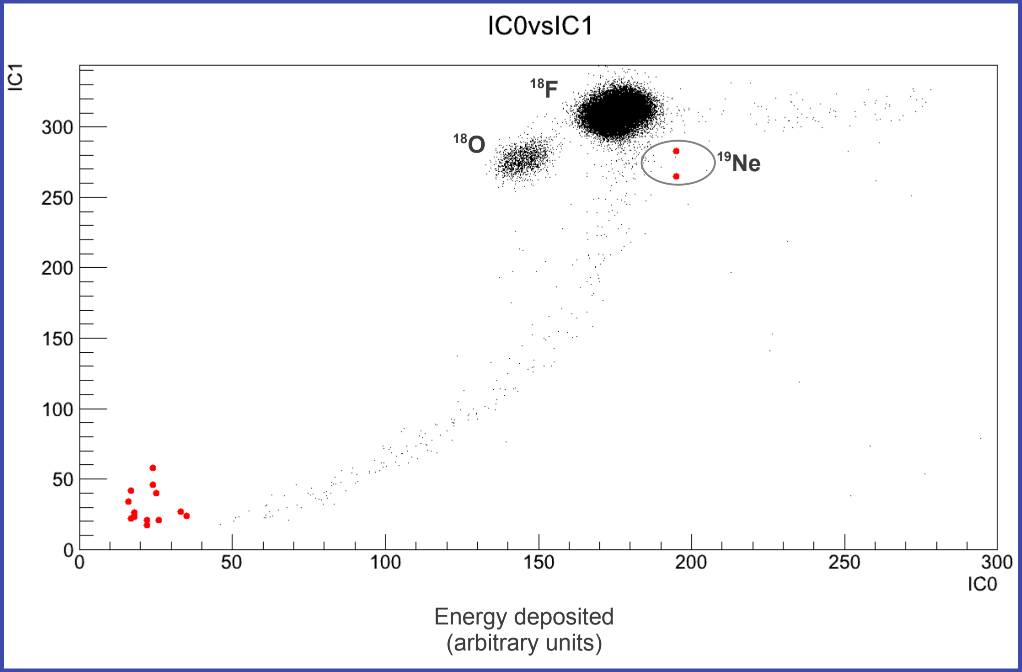
Measurement of (p,γ) at TRIUMF using DRAGON recoil separator



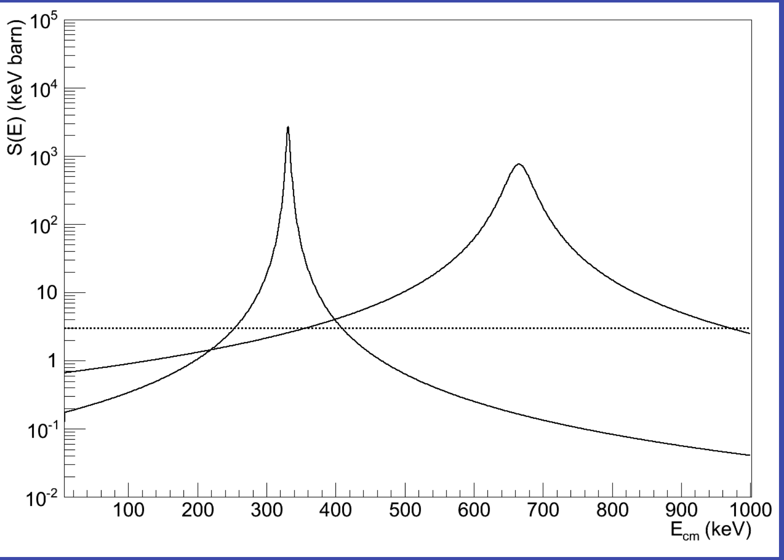
Measure using the standard DRAGON technique for capture reaction

- inverse kinematics: ^{18}F beam on hydrogen gas target
- detection of prompt gammas in BGO array
- selection of ^{19}Ne recoils through separator and detection in end detector

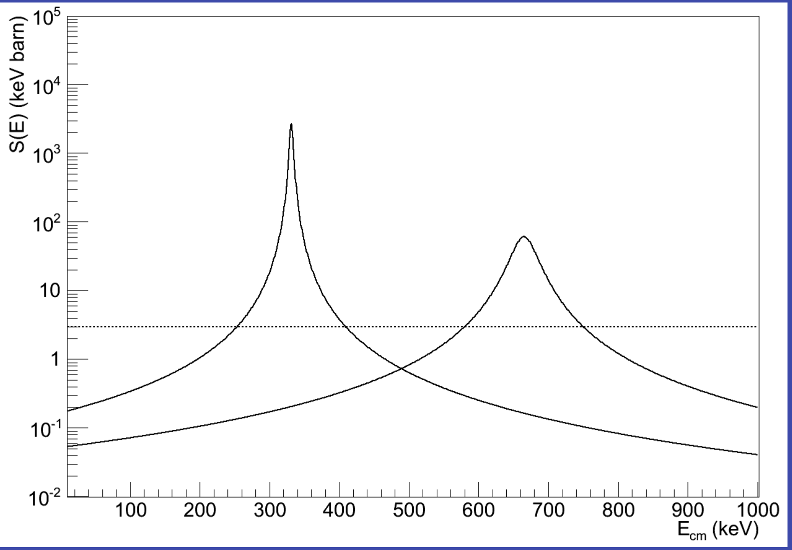
Initial plan was to measure 665 keV and 330 keV, but after one week only 2 counts in 665 keV



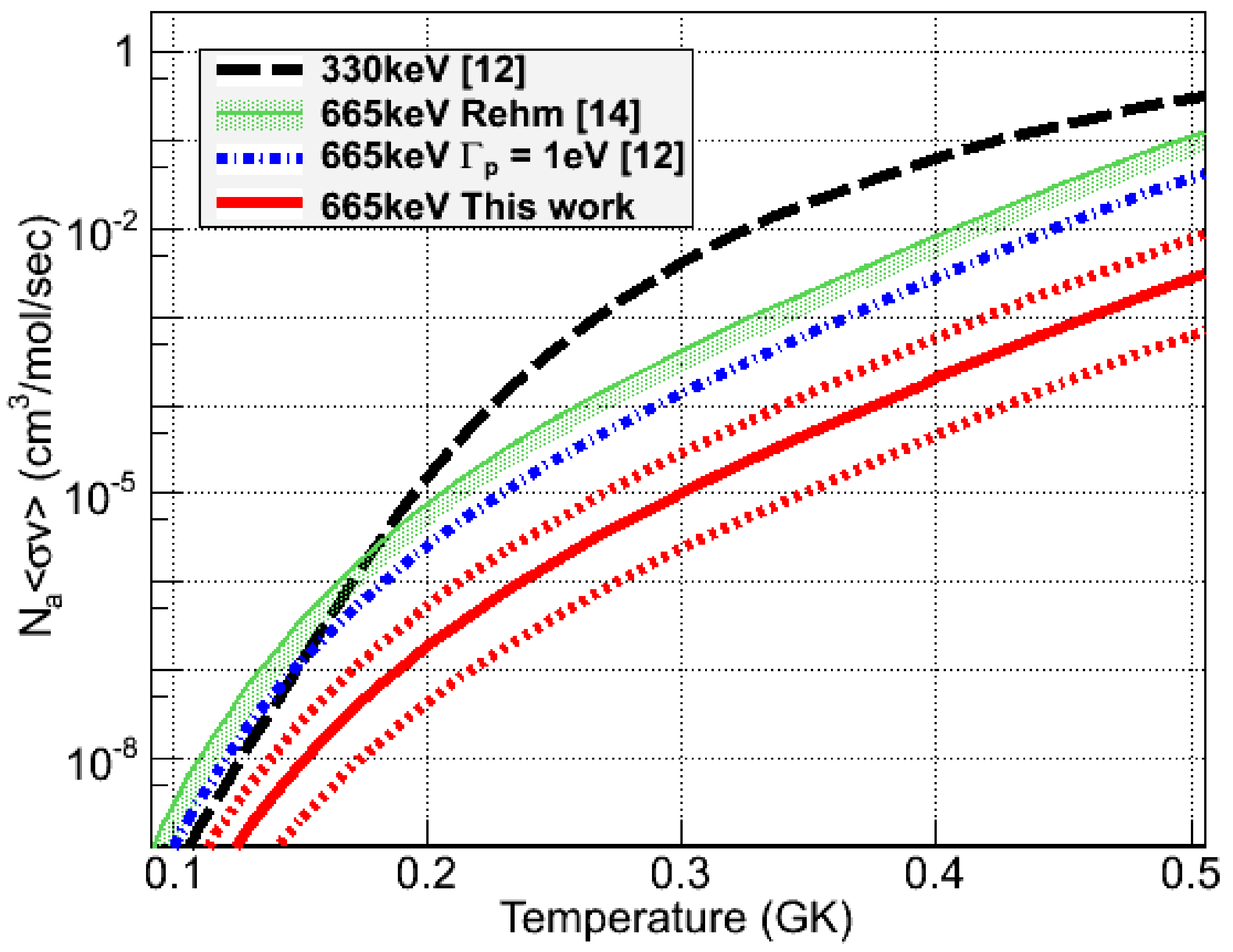
Strength of 665 keV x13 less than has been assumed in the past (but $\Gamma\gamma$ had only been a guess)



Previous assumed width



Width from this measurement

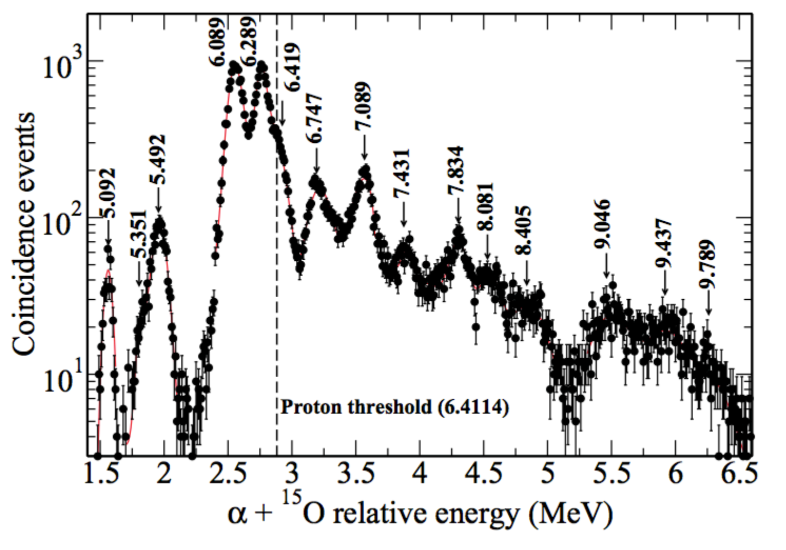


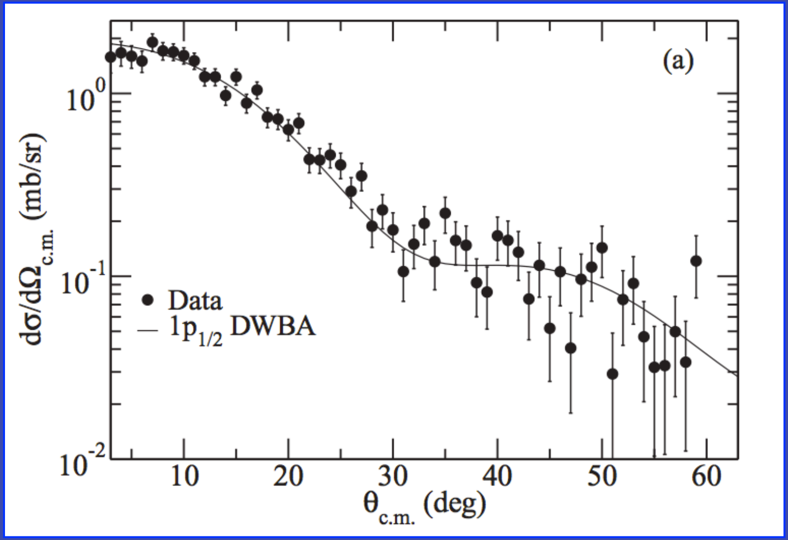
C Ackers et al. submitted to Phys Rev Letts

665 keV won't play any role so the (p,γ) rate will be dominated by the 330 keV, for which the $\Gamma\gamma$ is very uncertain and needs to be constrained

A (^{3}He,t) study of ^{19}Ne spectroscopy at Munich

As we looked closer at past data and analogue assignments we began to get worried





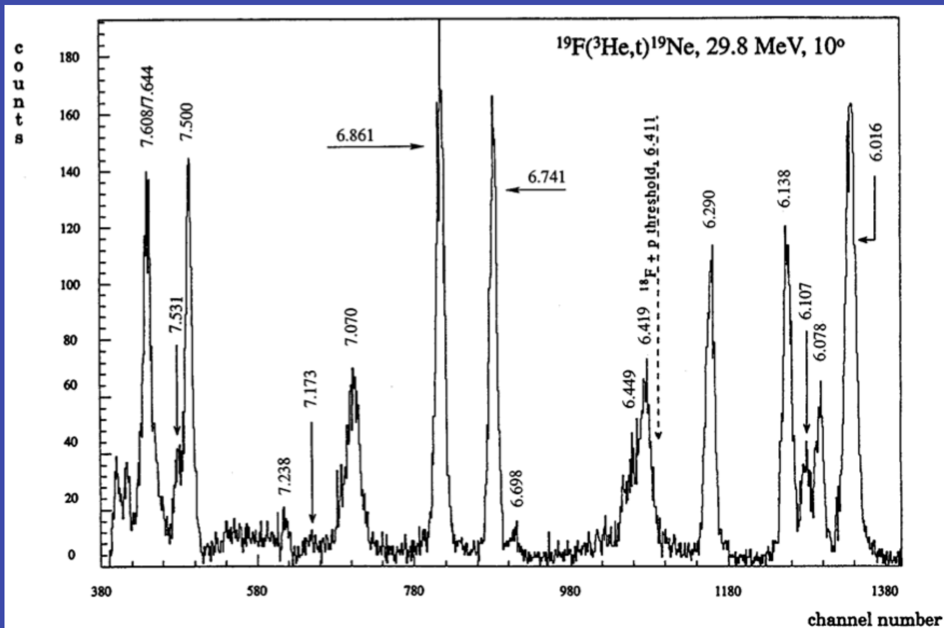
Concerns worsened when we saw recent results from Adekola et al. PRC(R) 83052801 (2012)

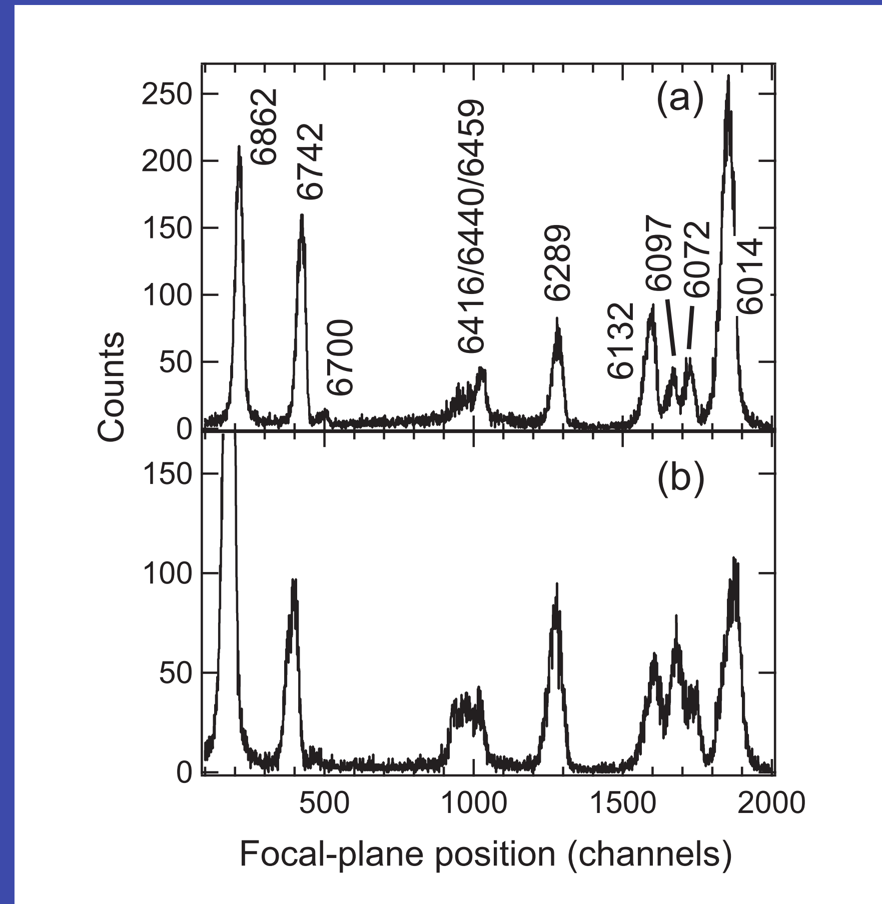
^{18}F(d,n)^{19}Ne*>^{15}O+α

- 38 keV not observed
- 8 keV populated
- 8 keV consistent with l = 1
  i.e. not l=0 (so not 3/2$^+$!)

=> no constraint on 38 keV J^{π}

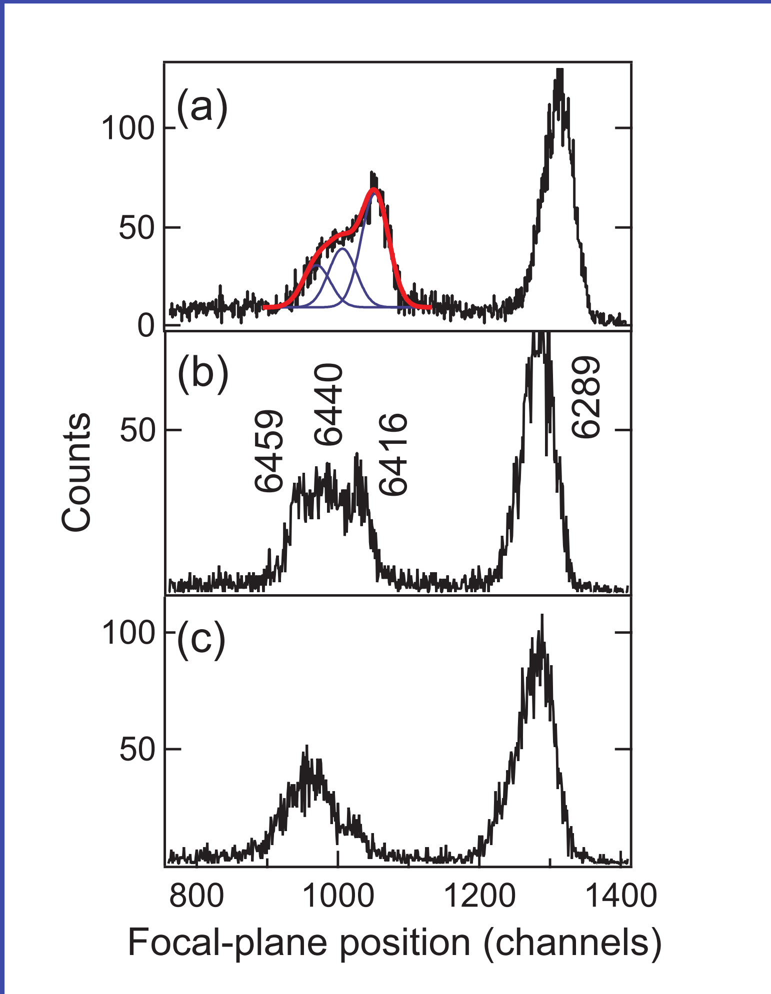
Aim - repeat Utku et al. measurement (Princeton Q3D) to check 8 and 38 keV states using Q3D at MLL in Munich



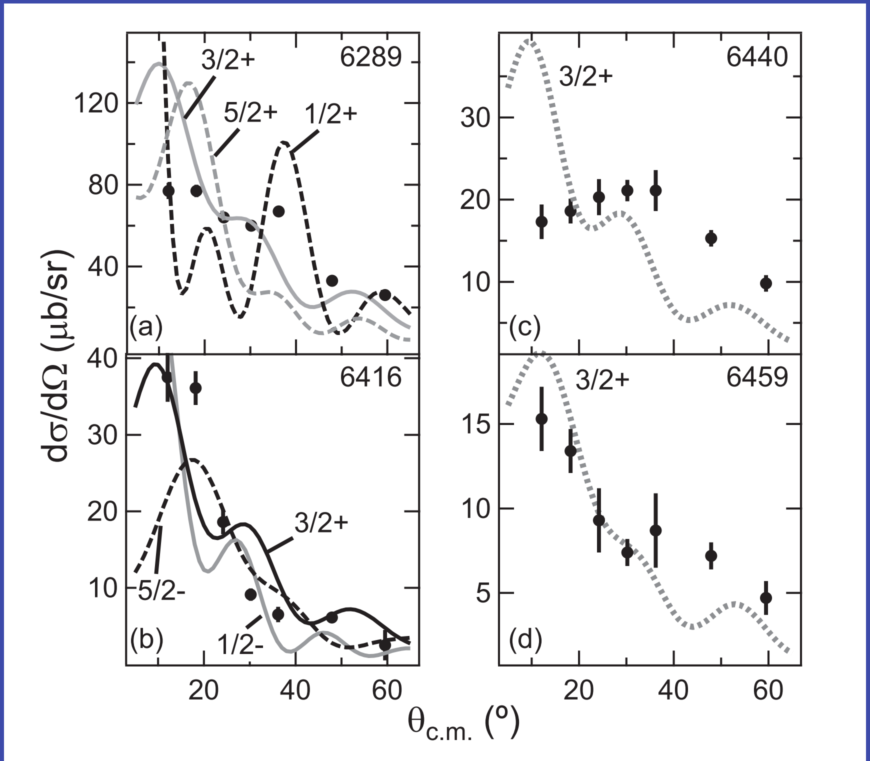


Excitation energy spectrum reproduced with slightly better resolution.

Angular distributions measured.



(a) 15° (b) 20° (c) 30°



The second results is that the angular distributions are all different and the 29 keV appears to have a high spin

So states cannot be the 3/2+ pair as assumed from the mirror – physics interpretation now wide open

The first result is that there are not two states just above threshold but three, at 5, 29 and 48 keV

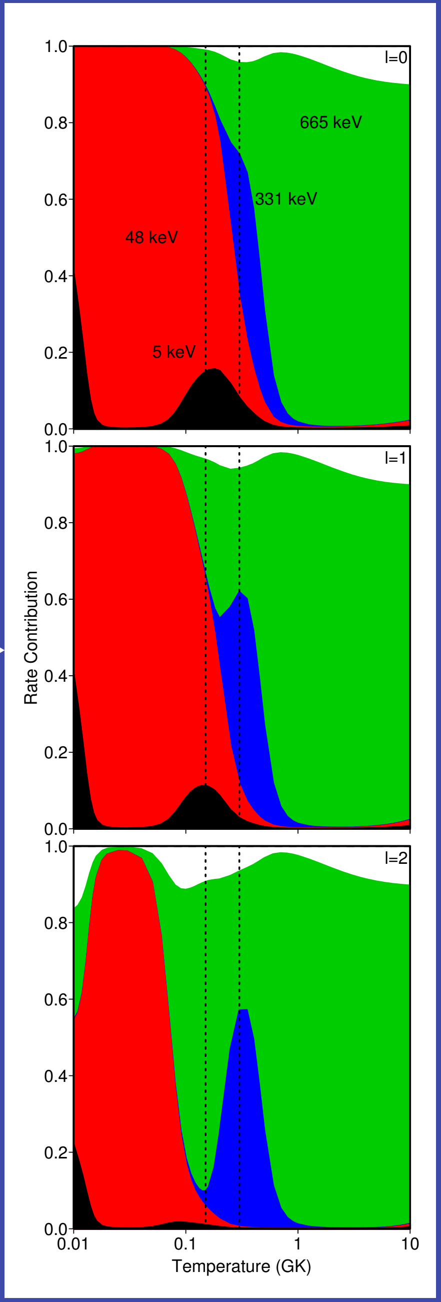
A M Laird et al. Accepted for Phys Rev Lett

So where are the 3/2+ states? Could be below threshold?

Crucial as interference of these with the broad 665 keV state can dominate the yield

Rate calculations show that the 5 keV will have little effect in the rate.

The 48 keV could be important if low spin



Reaction model calculation for charge exchange not ideal, so follow up measurement planned to get firm spin assignments with $^{20}Ne(d,t)^{19}F$

CONCLUSIONS

Satellite missions are searching for gamma emission from novae and the prime candidate is the 511 keV from ^{18}F decay which occurs immediately after the outburst

Sensitivity studies show the limitations on understanding the amount of ^{18}F (and hence the distance at which we can detect the emission) are the uncertainties on the $^{18}F(p,\alpha)$ and $^{19}F(p,\gamma)$ reaction rates.

We are close to getting direct measurements in the relevant energy range, but need further increases in beam intensity.

In the absence of direct measurements calculated rates have been used, but (a) there is a problem as the interference phases aren't known and (b) some of the main states included may have been miss assigned