Nucleosynthesis in Explosive Astrophysical Sites

Lecture 4

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In this last lecture we will look at some examples of recent studies of explosive nucleosynthesis.

Much of the current activity is in key reactions for novae and X-ray bursters, including the reactions that lead to breakout from the CNO-cycle

Have selected out work on novae to illustrate

^{22}Na production in novae

^{18}F production in novae

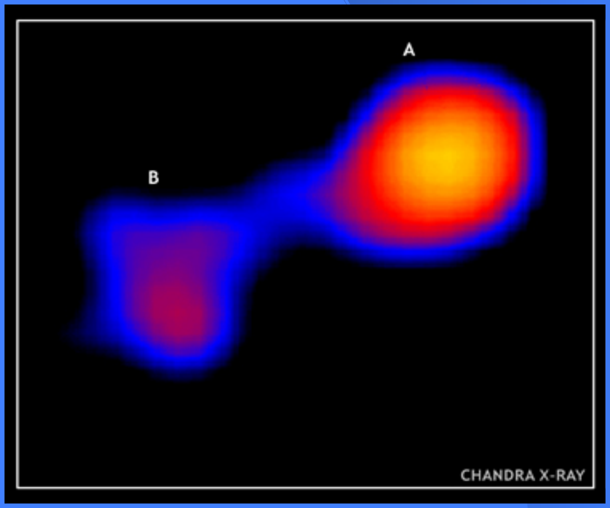
^{16}O as a poison for the s-process? (not really explosive, but nice physics)

Classical novae arise in binary systems where H accretion onto a CO or ONe White Dwarf occurs

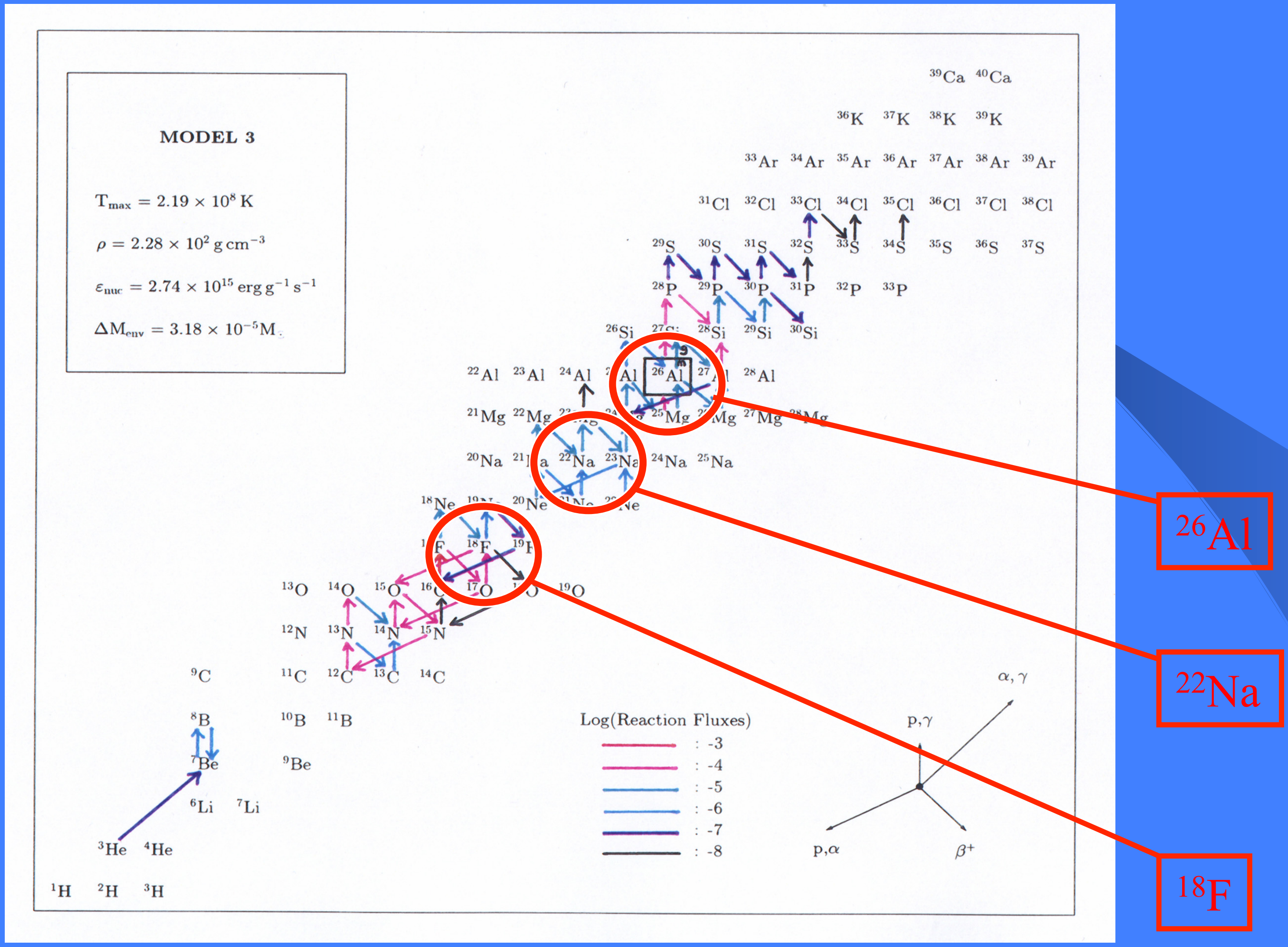
Information from light curves is limited as the spectra only give chemical composition at the end of the event

Gamma spectroscopy offers time resolved isotopic composition

^{13}N	862s	511keV	CO/ONe
^{18}F	158m	511keV	CO/ONe
^{7}Be	77d	478keV	CO
^{22}Na	3.75yr	1275keV	ONe
^{26}Al	1Myr	1809keV	ONe



Gammas emitted by long lived radioactive nuclei

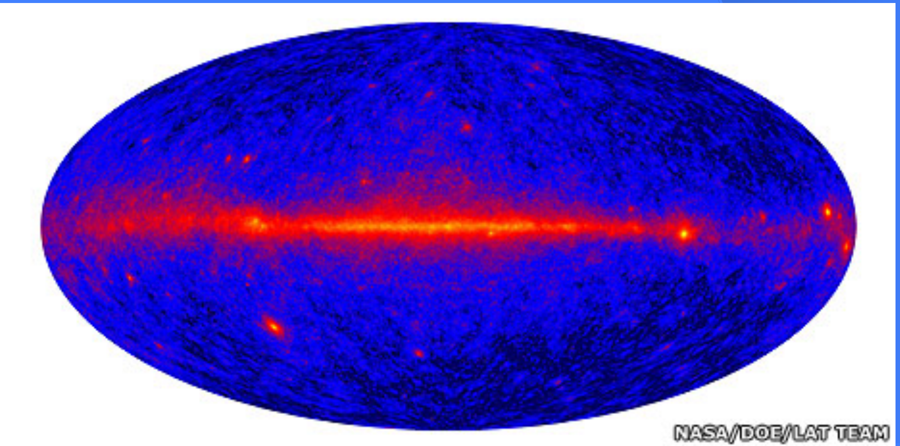


New gamma-ray observatories are capable of identifying specific nuclei from their characteristic gamma energies (e.g. ^{18}F, ^{22}Na, ^{26}Al, ^{44}Ti)

This will provide a stringent test on models, especially of Novae

INTEGRAL

GLAST (Fermi Telescope)



An example ^{22}Na production in novae

COMPTEL measurements of ^{22}Na in Her1991 and Cyg1992 are below expected limits

Models wrong?

Nuclear physics rates wrong?

Recent calculations (Jordi et al.) suggest a 1.25 solar mass White Dwarf Nova can eject 6.3×10^{-9} solar mass of ^{22}Na

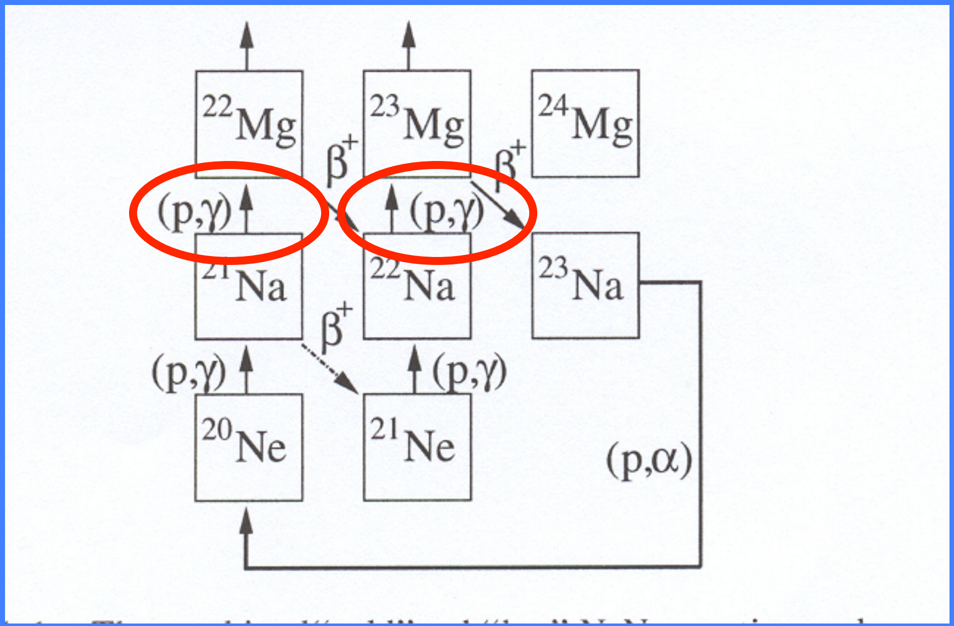
$T_{1/2} = 3.75$ yr

$E\gamma = 1.275$ MeV

With INTEGRAL should be able to detect out to 1 kpc
(about two thousand, million, million miles)

BUT: uncertainties in reaction rates give an uncertainty in production rate (and so chances of observing)

Production and destruction of ^{22}Na



Combined "Hot" and "Cold" Ne-Na cycles

Key reactions:

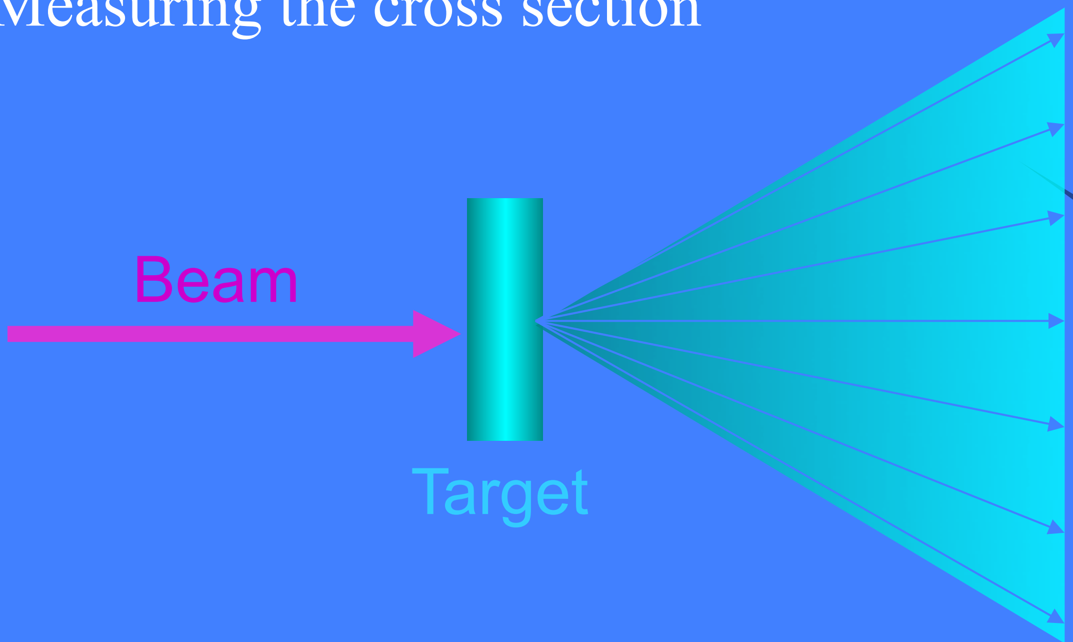
^{21}Na+p > ^{22}Mg+γ **(increased production)**

^{22}Na+p > ^{23}Mg+γ **(decreased production)**

Production reaction

Measuring the cross section

$^{21}Na(p,\gamma)^{22}Mg$

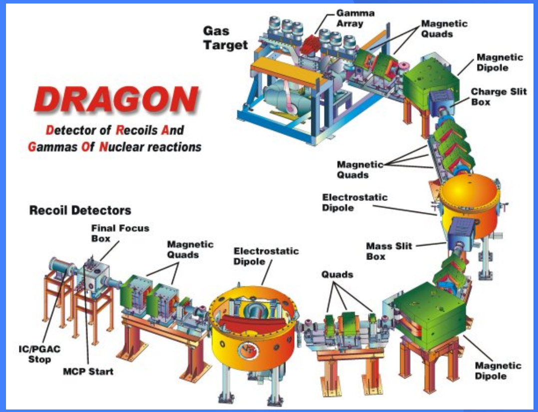


Beam of ^{21}Na
Target of Hydrogen

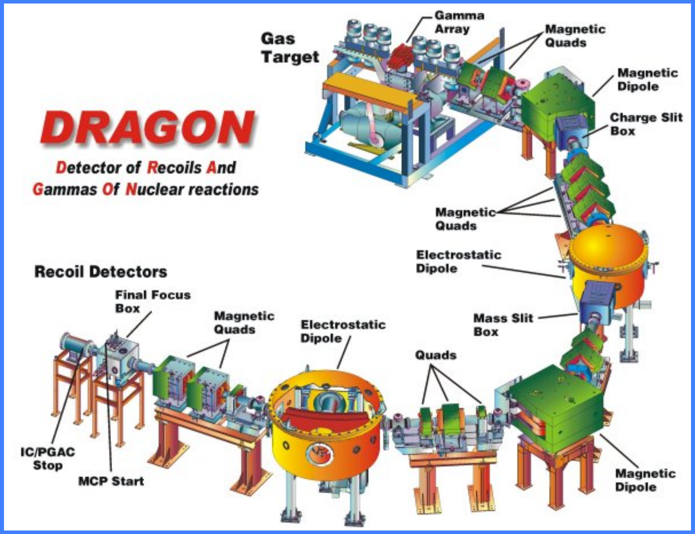
Need to detect either the γ-rays or the recoiling ^{22}Mg

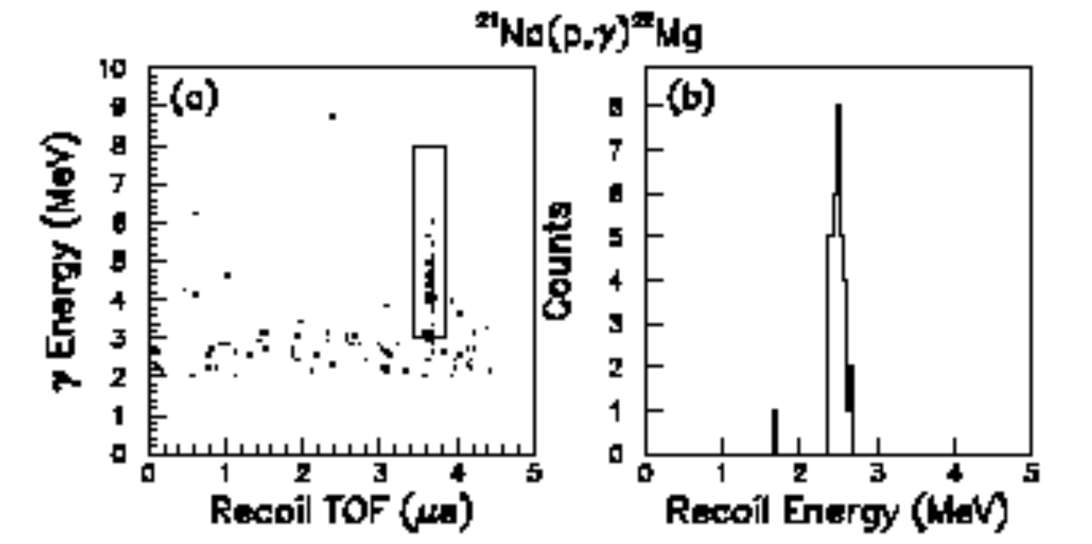
..or both

Know number of beam particles
Know number of target nuclei
Measure number of nuclei created
Probability > Cross section

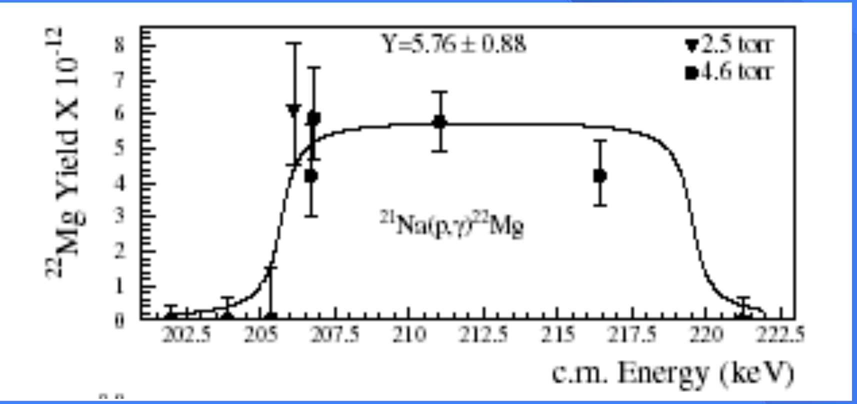


Production reaction





Cross section is
larger than thought
at low energies



Updated calculations (J.Jose) show ^{22}Na production occurs earlier while envelope is still hot and dense enough for it to be destroyed

So lower final abundance of ^{22}Na

Destruction reaction

^{22}Na(p,γ)^{23}Mg

This time we calculate the rate rather than measure it.

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

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

for $\Gamma_p << \Gamma_\gamma$:

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

For this need to know all the levels in ^{23}Mg – energy, spin and gamma decay widths

So do detailed spectroscopic study on ^{23}Mg

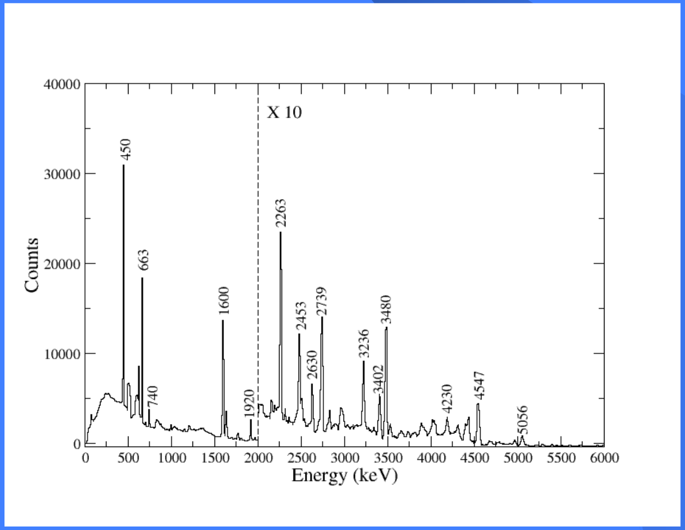
Destruction reaction

"Brute Force" spectroscopy of ^{23}Mg using Gammasphere and the $^{12}C(^{12}C,n)$ reaction.

Determined levels and widths for states just above threshold

Very high statistics data set

- improve resonance energies
- fix unknown spins and parities
- identify new threshold state
- determine lifetimes (widths)



Recalculate the reaction rate with this updated information and get x10^2 greater rate

So again, a lower final abundance of ^{22}Na

Feed through same Nova model gives factor of 3 less ^{22}Na

So chances of observing a ^{22}Na signal from Nova from satellite missions may be considerably less that anticipated

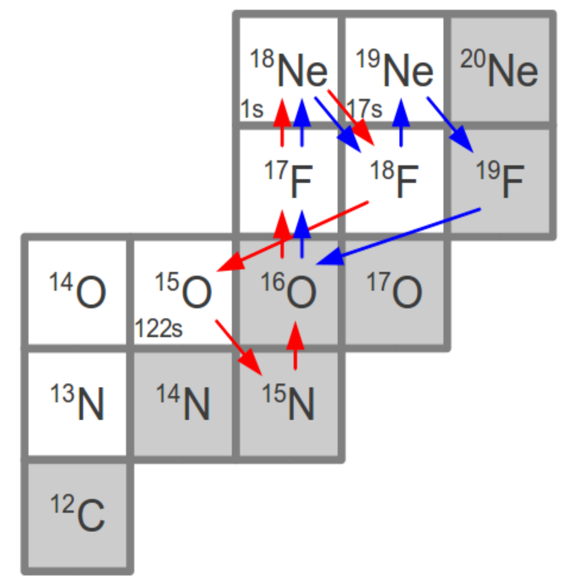
^{18}F production in novae

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. So the models require reaction rate (cross section) to be measured over a range of energies

Because of the lack of an ^{18}F beam, no (p,α) or (p,γ) measurements exist that extend into the energy region relevant for novae

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

which needs energies, spins and partial widths of the relevant states

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.

Previous calculations assume rate dominated by the following low spin states (the centrifugal barrier will limit the contribution from higher spin states)

665 keV 3/2+	(p,α) measured by Bardayan et al. No Γγ
330 keV 3/2-	(p,α) measured by Bardayan et al. No Γγ
8 and 38 keV 3/2+	Spin and widths guessed from proposed analogues

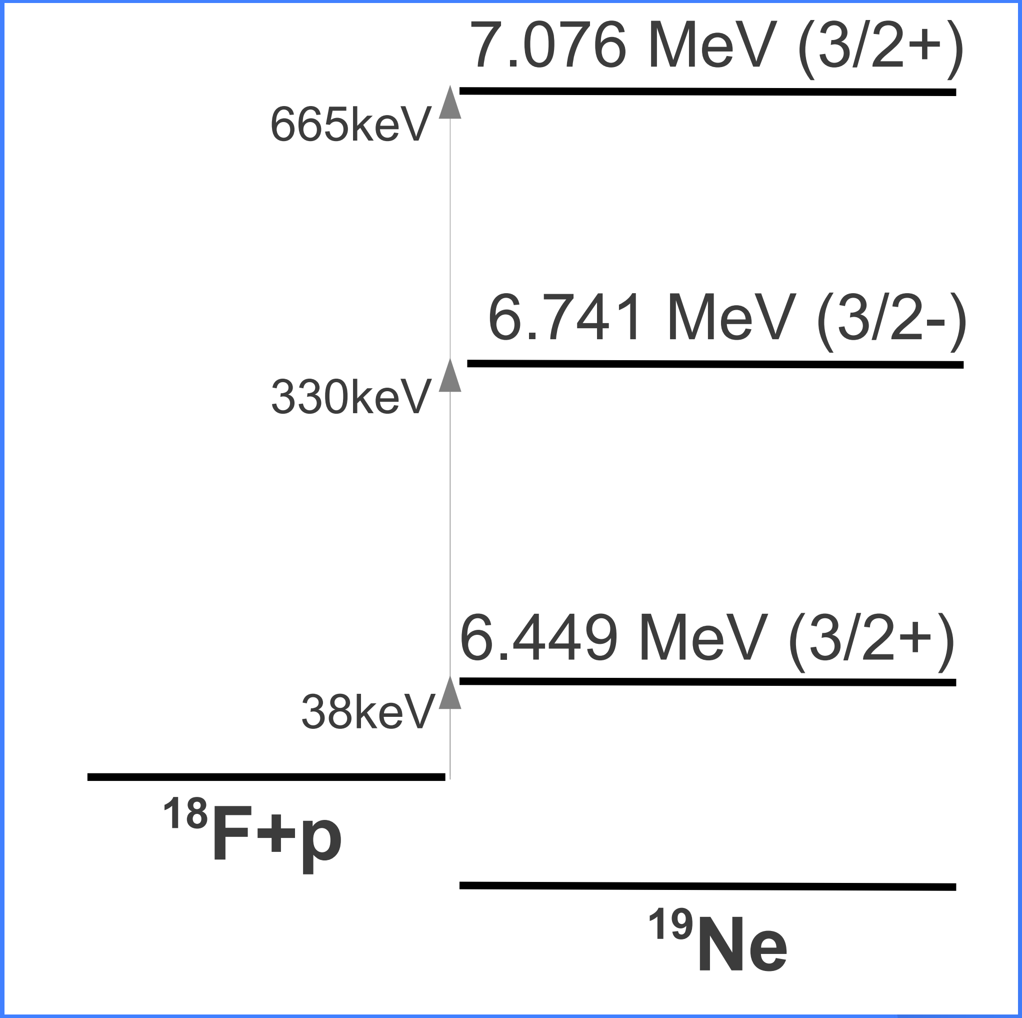
and some possible low spin sub threshold states (no spins or widths)

Main low spin states thought to dominate capture rate

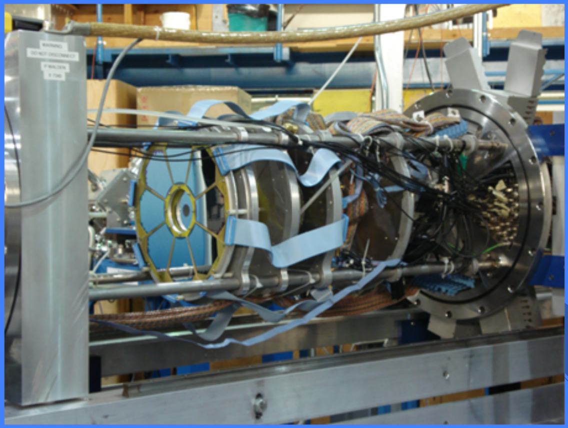
38 keV associated with ^{19}F analogue at 6.528MeV with $\Gamma\gamma$ = 1.1+/-0.6 eV

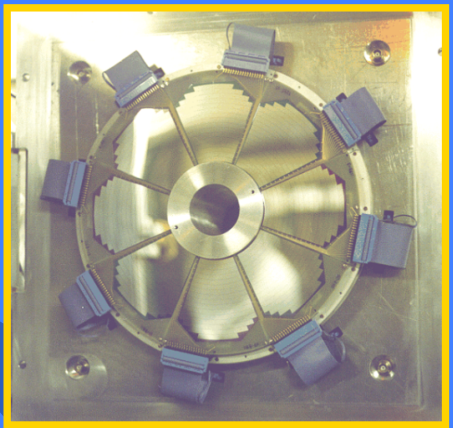
330 keV associated with ^{19}F analogue at 6.787MeV with $\Gamma\gamma$ = 5+/-3 eV

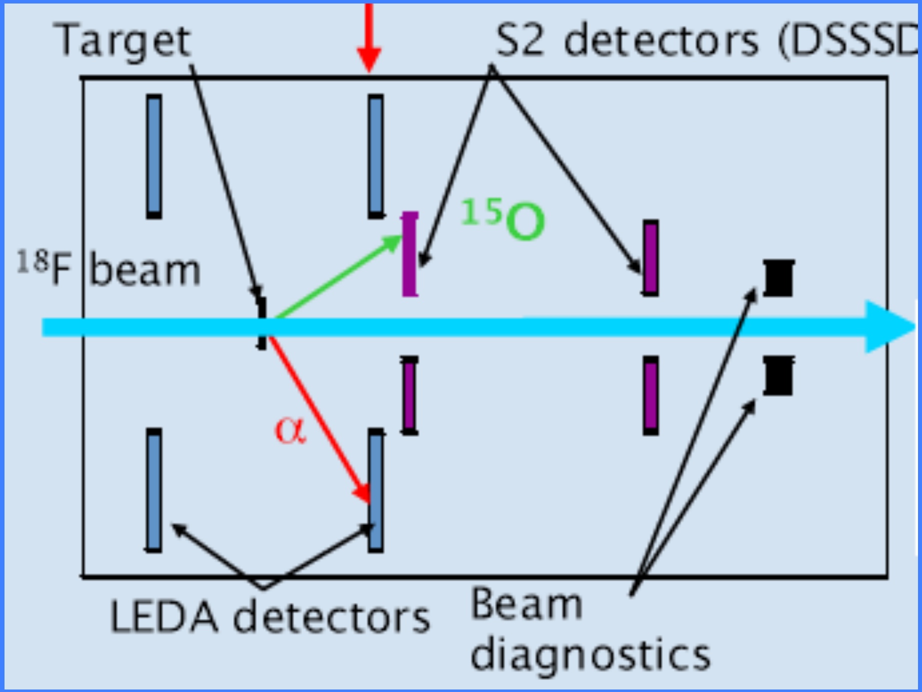
665 keV not been associated with any ^{19}F analogue. Nesaraja assumed $\Gamma\gamma$ = 1eV based on average of nearby states



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

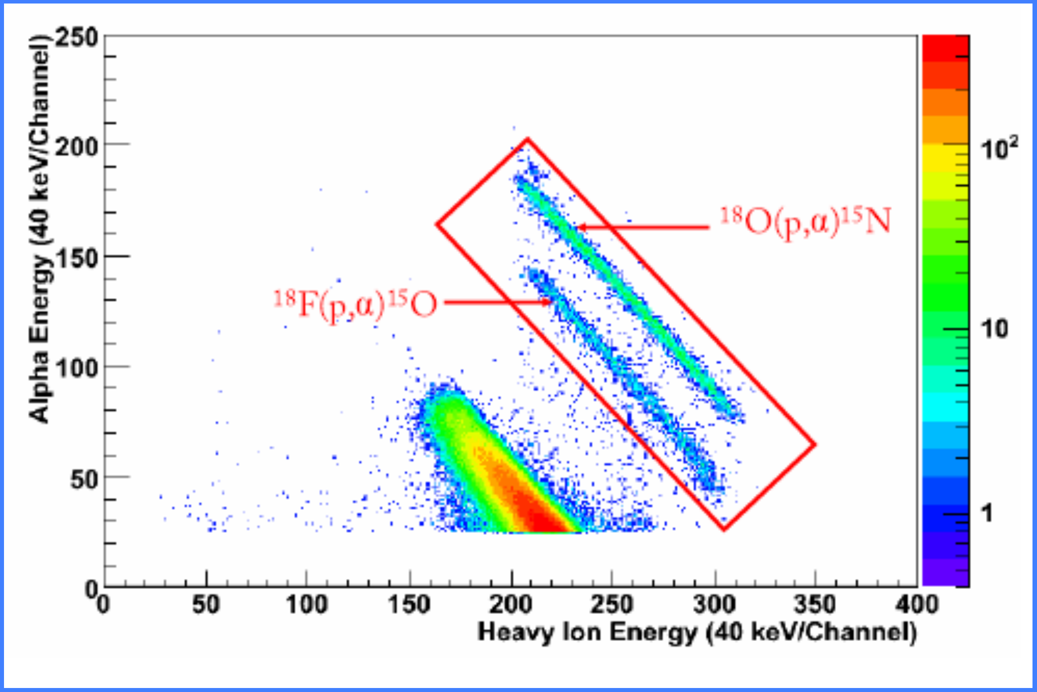






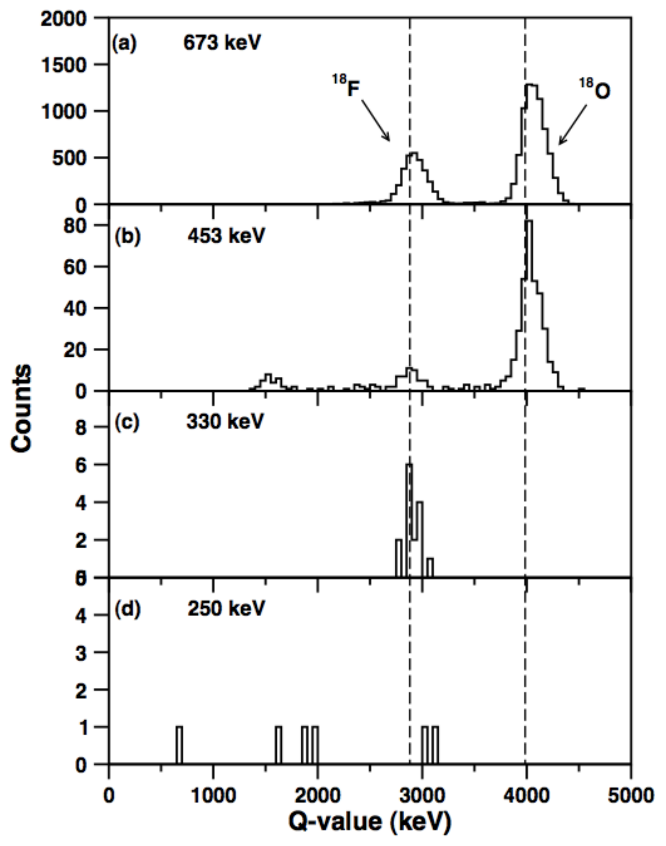
TUDA Array

Array of segmented annular silicon detectors

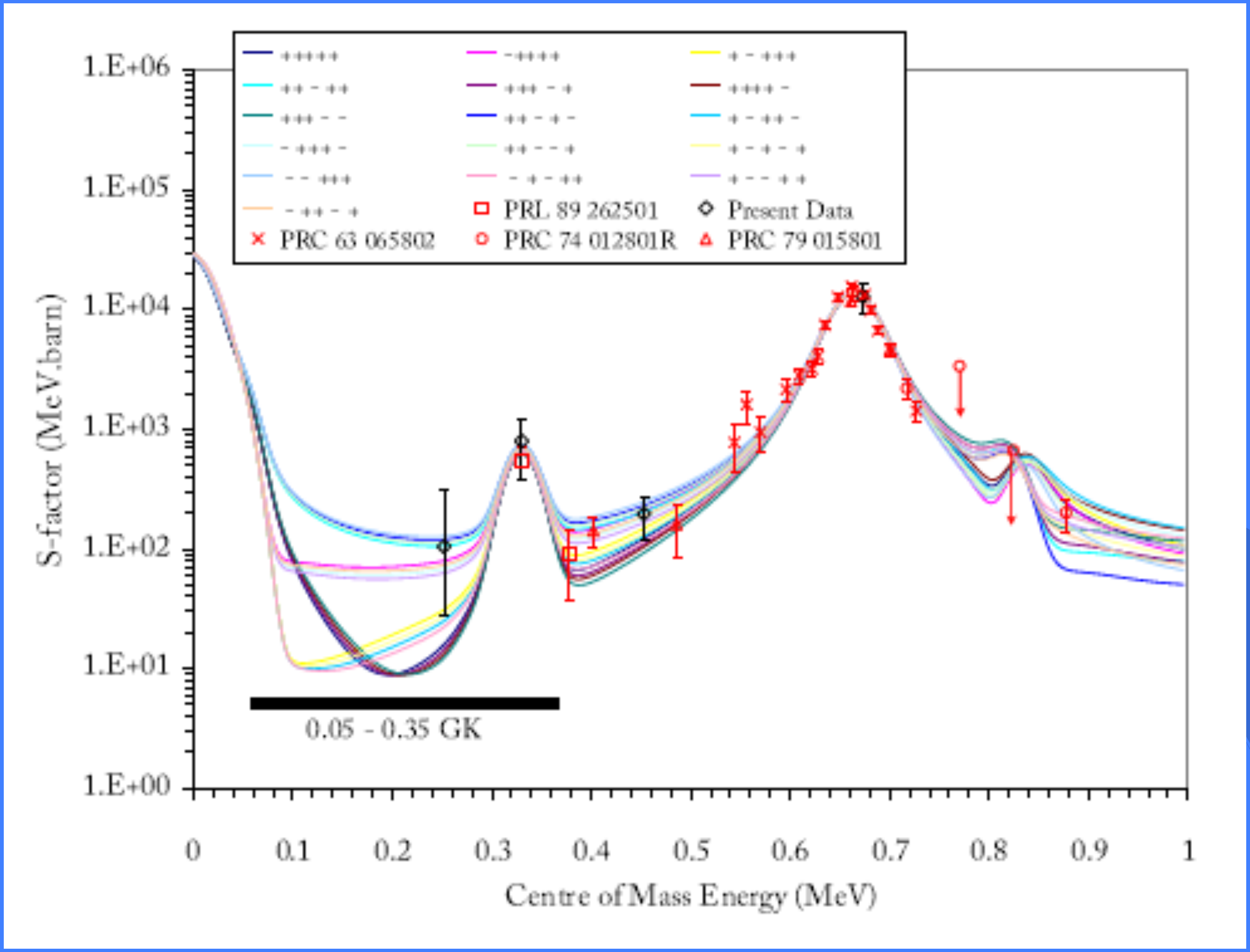


E_{beam} = 12.96 MeV

Kinematic coincidence allows rejection of ^{18}O contaminant beam



E_{α} for four beam energies



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

C E Beer et al
Phys Rev C83 042801(R) 2011

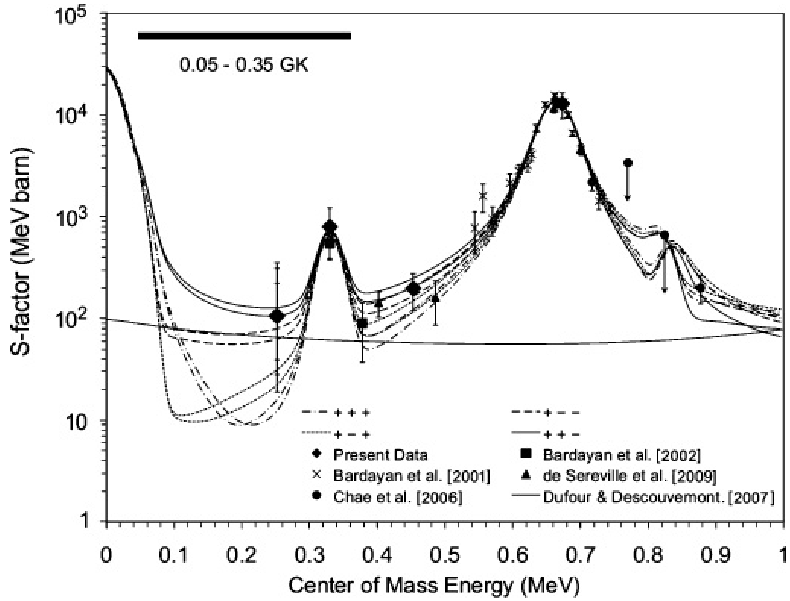


FIG. 3. The $^{18}F(p,\alpha)^{15}O$ S factors, calculated using the R matrix, for eight possible interference terms. The range in possible S factors arises from the interference between the $J^{\pi} = 3/2^{+}$ resonances. The interference between resonances dominates in the region of interest, resulting in four groups of S-factor curves. The upper and lower curves of each group are shown in the figure. The legend gives the assumed phase, for the 8-, 38-, and 665 keV resonances, respectively, for each pair of curves. Also plotted are the measured S factors from this work, those from previously published data [4,10,12,19], and the proposed contribution from $1/2^{+}$ states predicted in Ref. [6].

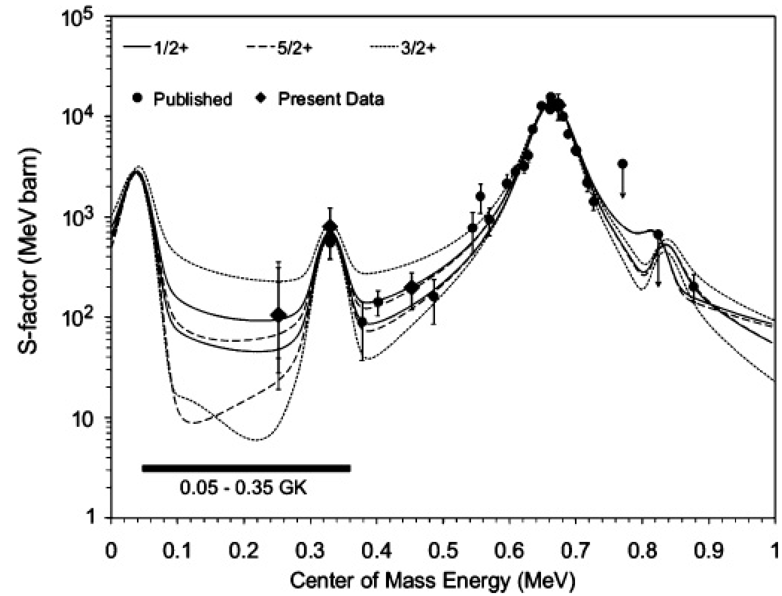
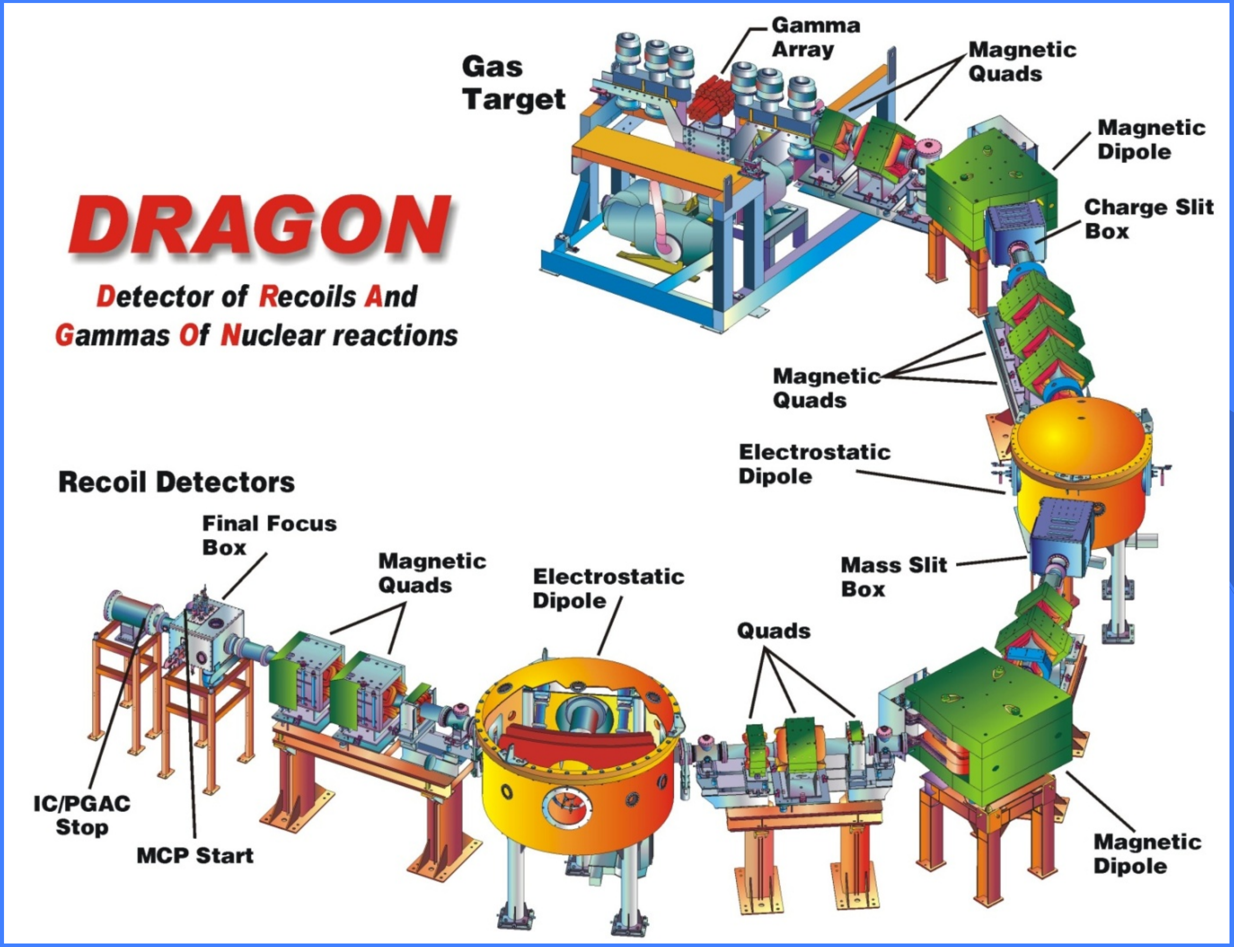


FIG. 4. Calculated $^{18}F(p,\alpha)^{15}O$ S factors with the 8 keV state treated as having a spin-parity of $3/2^{-}$ using the Adekola parameters [9]. The six curves correspond to the upper and lower S factors, assuming the -121 keV resonance to be $1/2^{+}$, $5/2^{+}$, or $3/2^{+}$.

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?

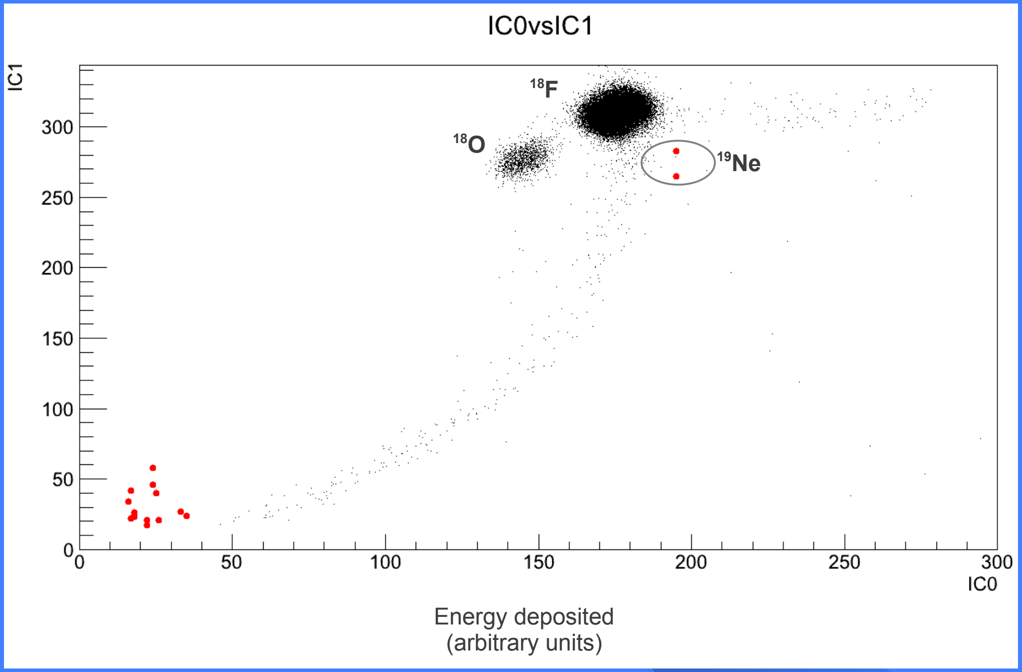
Measurement of (p,g) at TRIUMF using DRAGON recoil separator



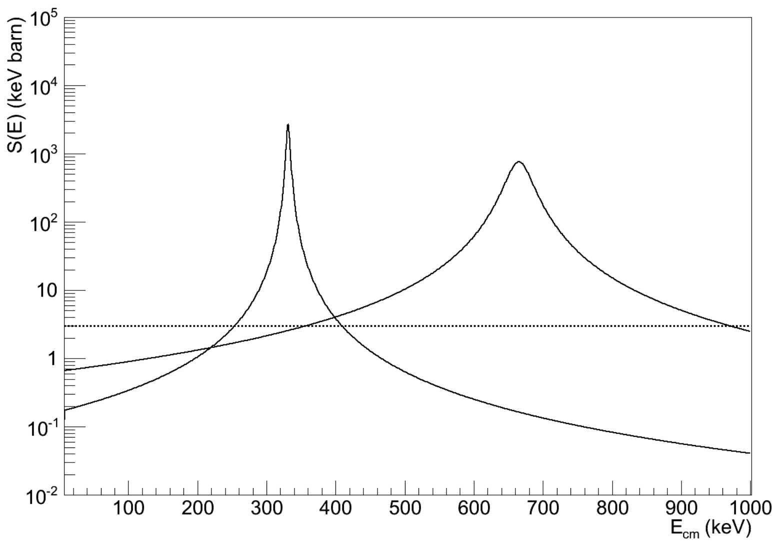
Measure using the standard DRAGON technique for capture reaction

- 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

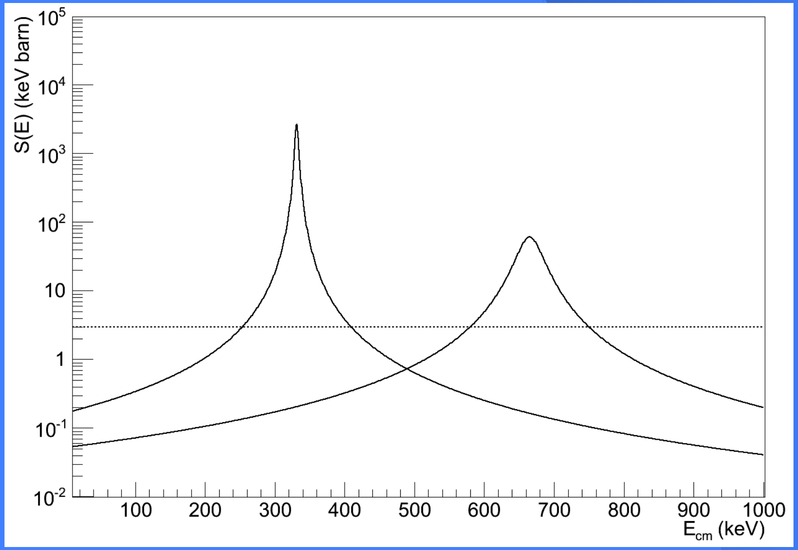
Initial plan was to measure 665 keV and 330 keV, but after one week only 2 counts in 665 keV



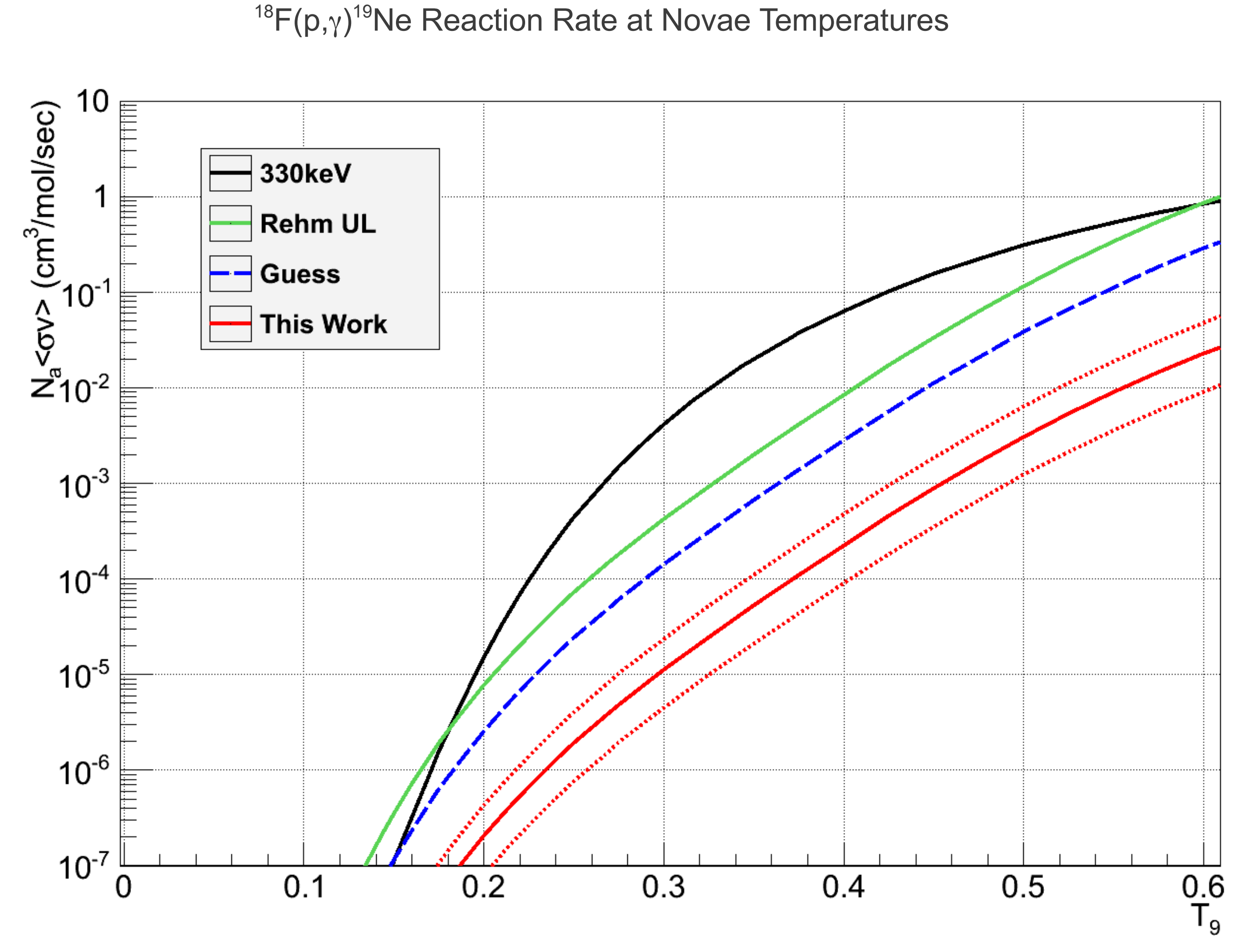
Strength of 665 keV x13 less than has been assumed in the past (but Γ_γ had only been a guess)



Previous assumed width



Width from this measurement

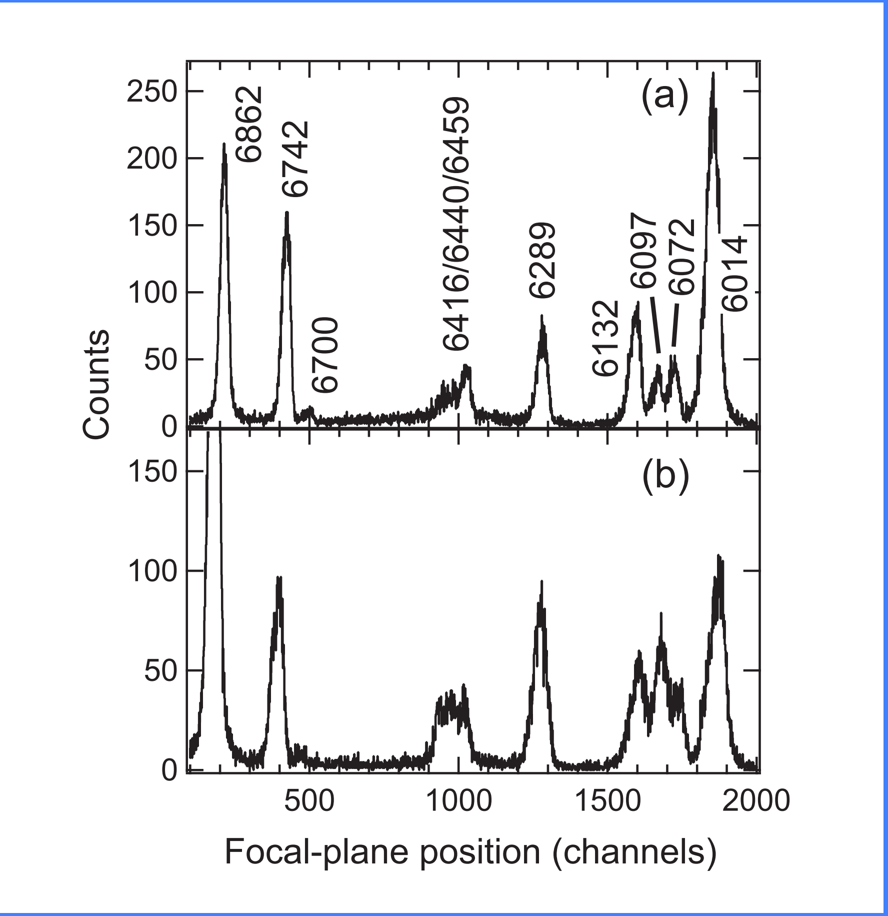


665 keV won't play any role so the (p,γ) rate will be dominated by the 330 keV, for which the Γγ is very uncertain and needs to be constrained

Measurement of 330 keV planned for next year

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

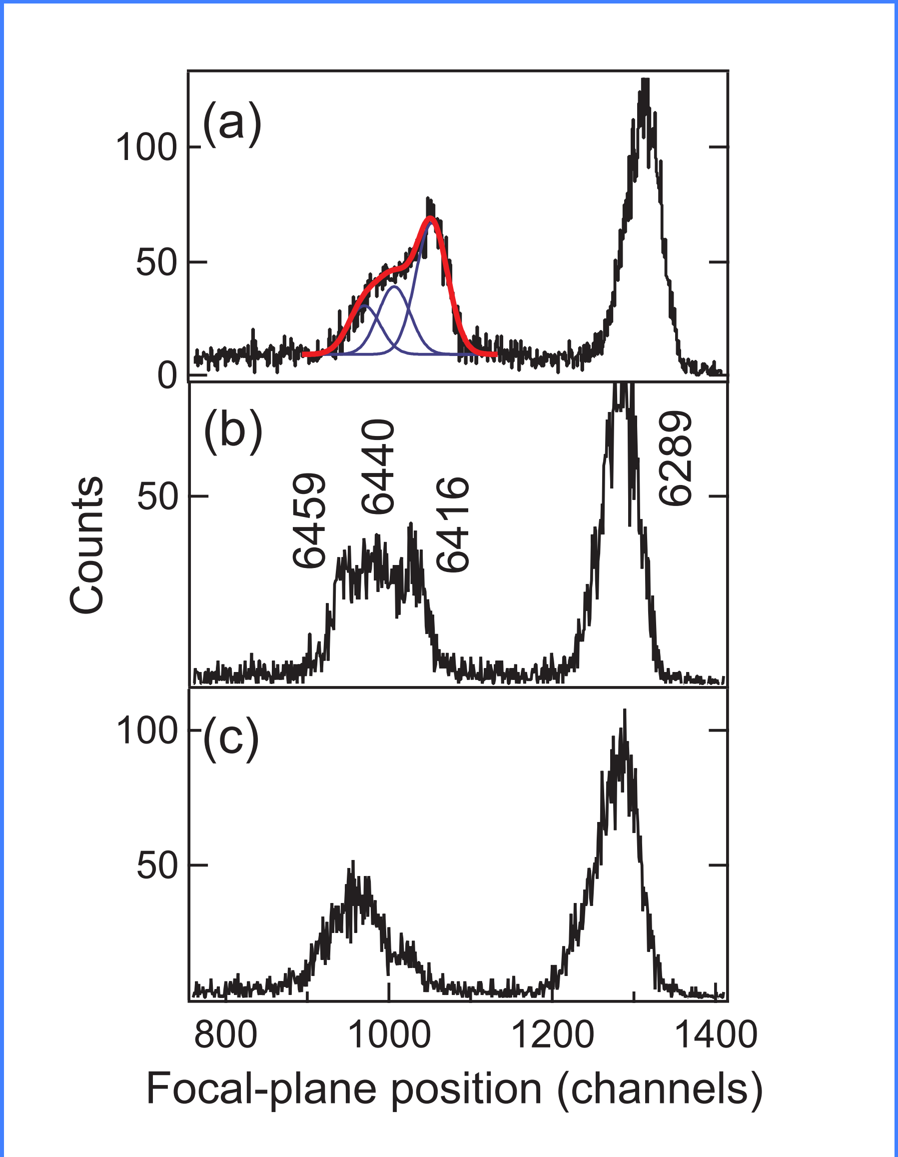
As we looked closer at past data and analogue assignments we began to get worried



So carry out high resolution measurement of $^{19}F(^3He,t)^{19}Ne$ reaction at Munich using the magnetic spectrometer.

(a) 10°
(b) 20°

PRELIMINARY DATA
Just submitted for publication

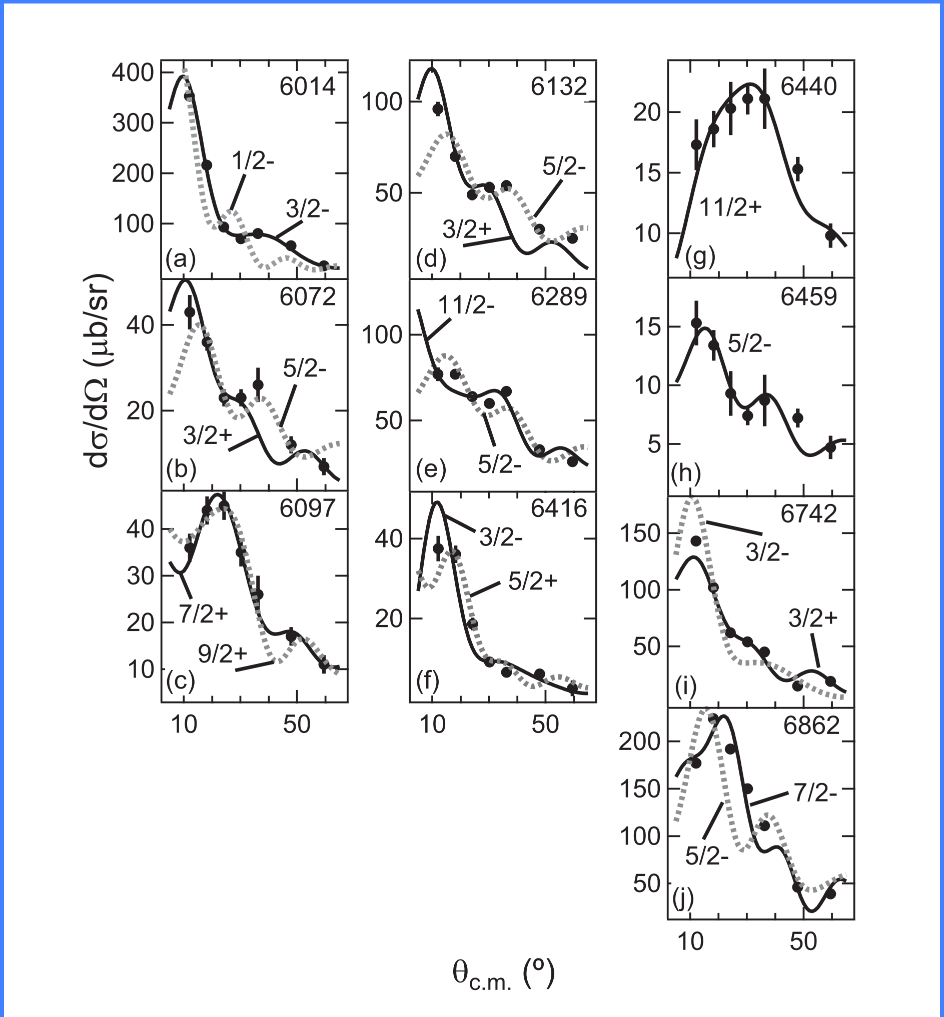


The first result is that there are not two states just above threshold at 8 and 38 keV

Rather, we find three states corresponding to resonances at energies of 5, 29 and 48 keV

PRELIMINARY DATA

(a) 15° (b) 20° (c) 30°



The second result is that the angular distributions don't seem to be consistent with 3/2+ as was assumed (although looking back the analogue assignment was rather vague)

Also, there are other possible low spin states around the threshold

PRELIMINARY DATA

Reaction model calculation for charge exchange not ideal, so follow up planned to get firm 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

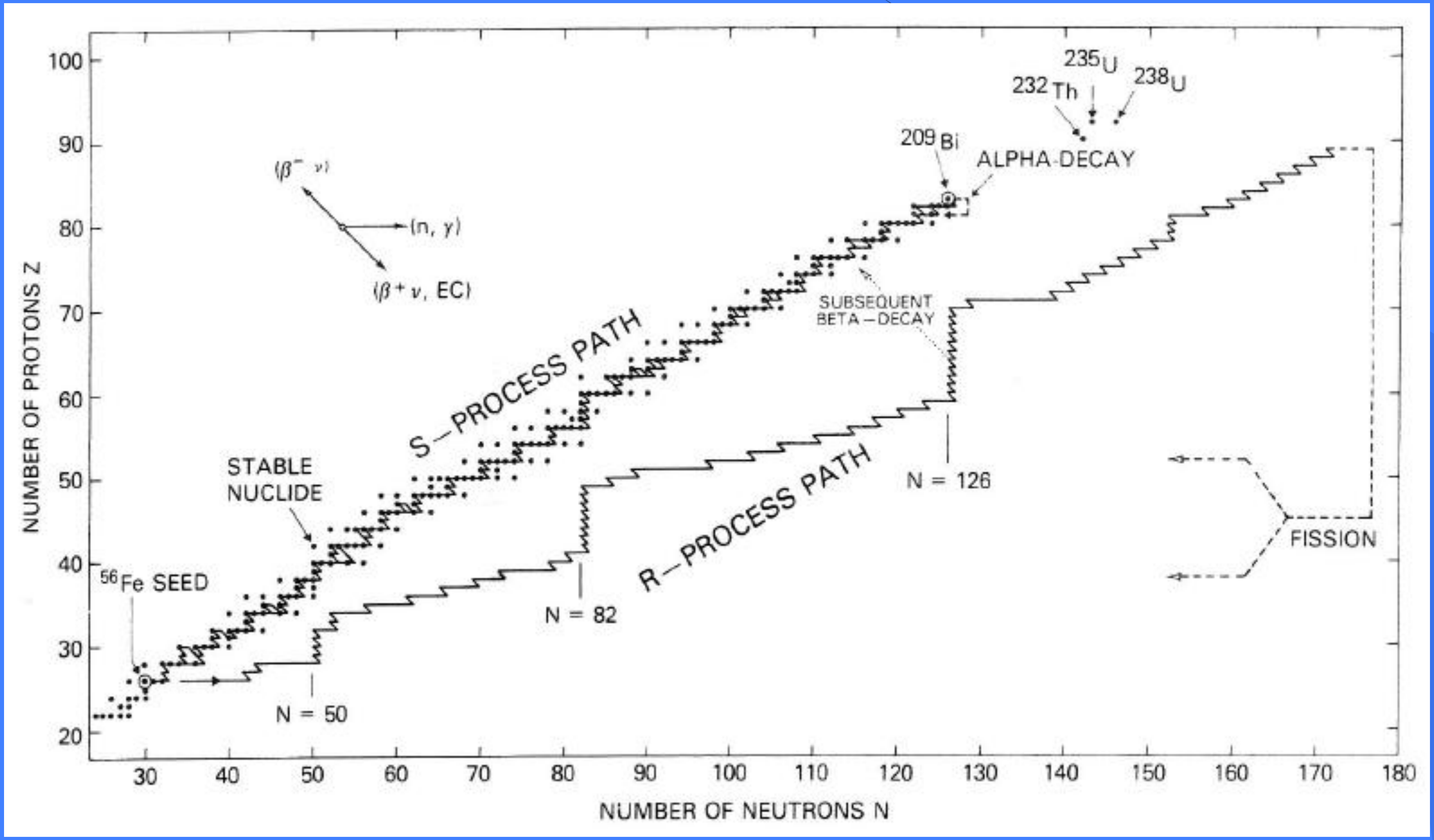
Sensitivity studies show the limitations on understanding the amount of ^{18}F (and hence the distance at which we can detect the emission) are the uncertainties on the $^{18}F(p,\alpha)$ and $^{19}F(p,\gamma)$ reaction rates.

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

Is this why no gamma emission has been observed to date?

s-process abundances



Physics interest

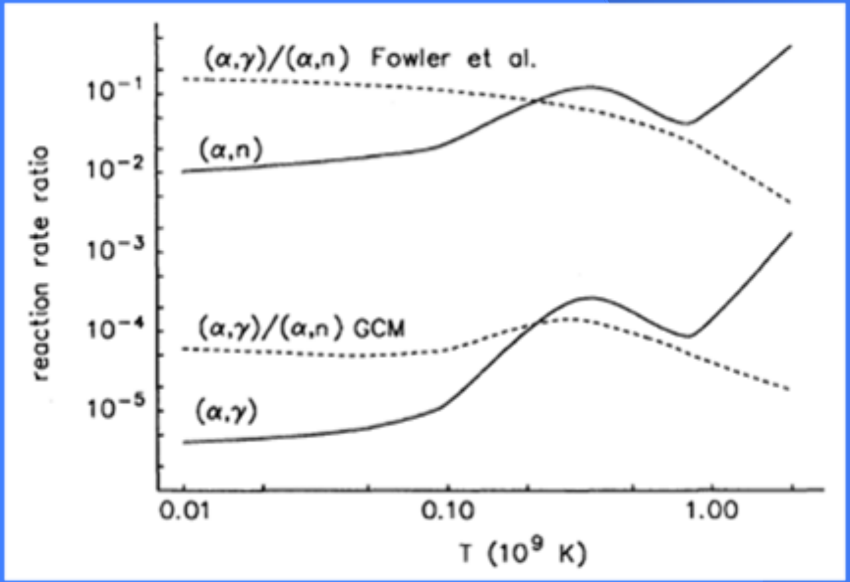
Weak s-process can run in massive stars at low metallicity, providing rotation provides mixing.

However ^{16}O in the star can act as a neutron poison – n capture on the ^{16}O to form ^{17}O removes the neutrons before they can participate in s-process

But in these stars there is a lot of helium, and alpha capture on the ^{17}O can lead to two outcomes depending on ratio of the $^{17}O(\alpha,\gamma)$ and $^{17}O(\alpha,n)$ reaction rates

$^{17}O(\alpha,\gamma)$	neutron lost
$^{17}O(\alpha,n)$	neutron returned

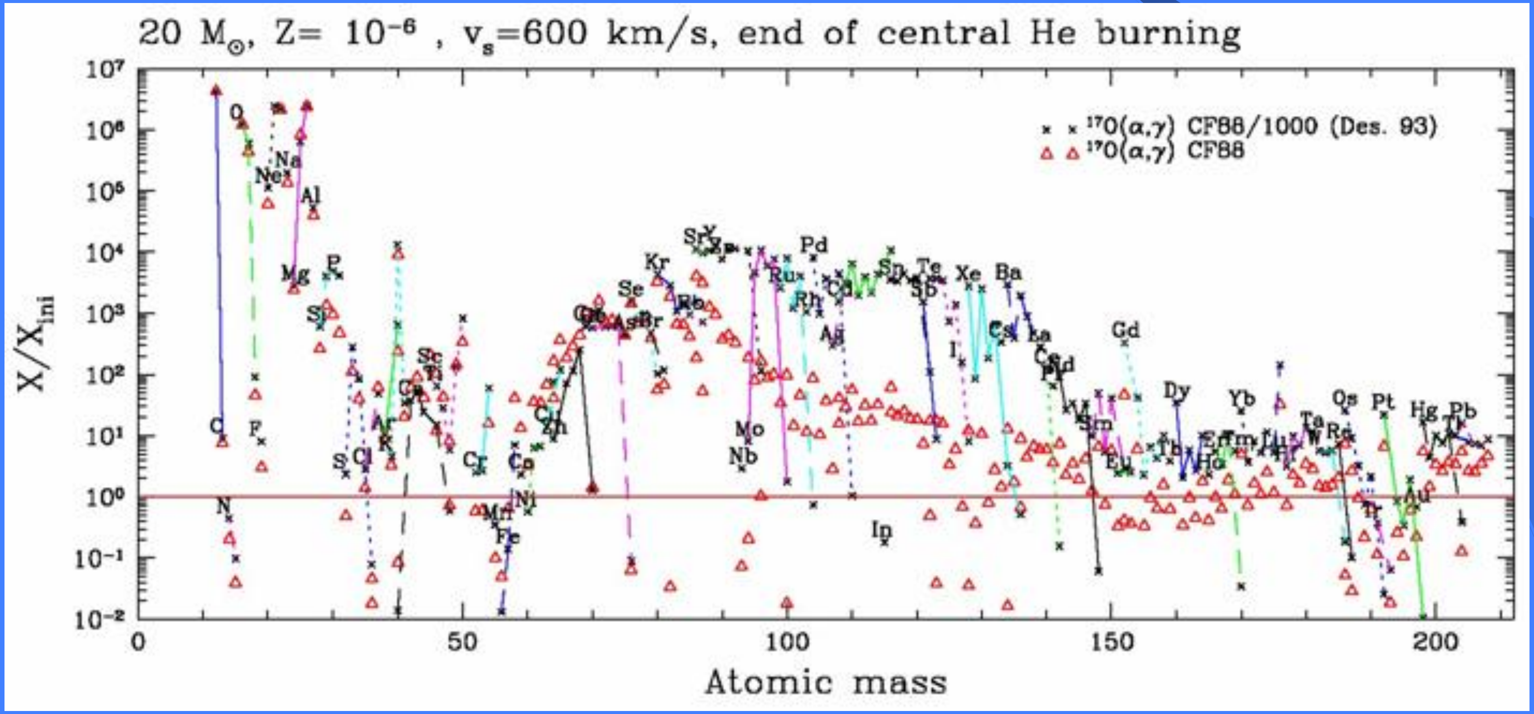
No experimental measurement but two conflicting predictions for this ratio which differ by a factor of 10^4 – causes big differences in yields in the Sr to Ba region



Phys. Rev. C, 48, 2746 (1993

$^{17}O(\alpha,n)$ measured, but still have 10^4 variation for (α,γ)

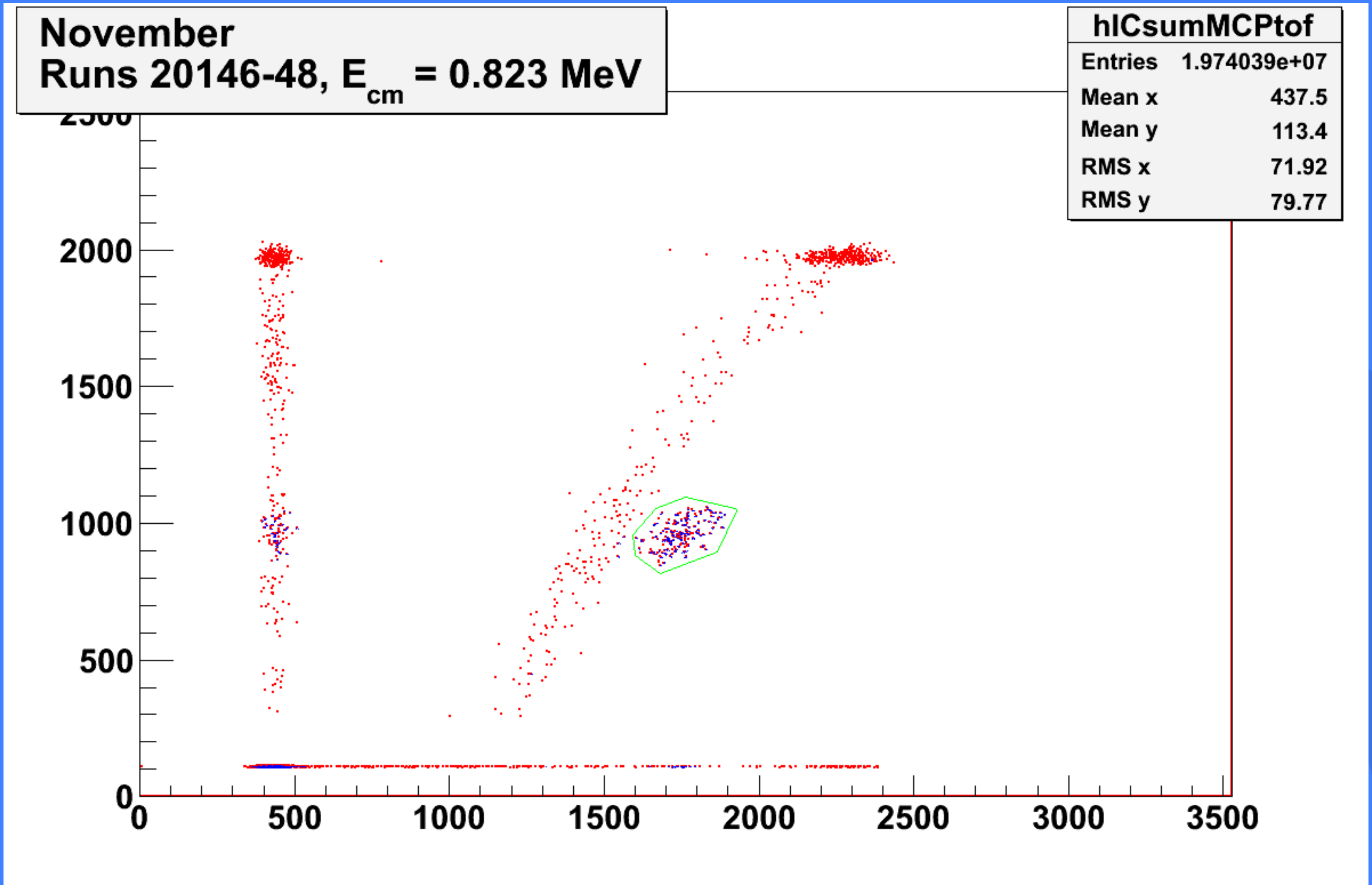
- Calculations of the "weak" component of the s-process in massive stars at low metallicity with the different rates for $^{17}O(\alpha,\gamma)^{21}Ne$, produce vastly different abundances from Sr to Ba

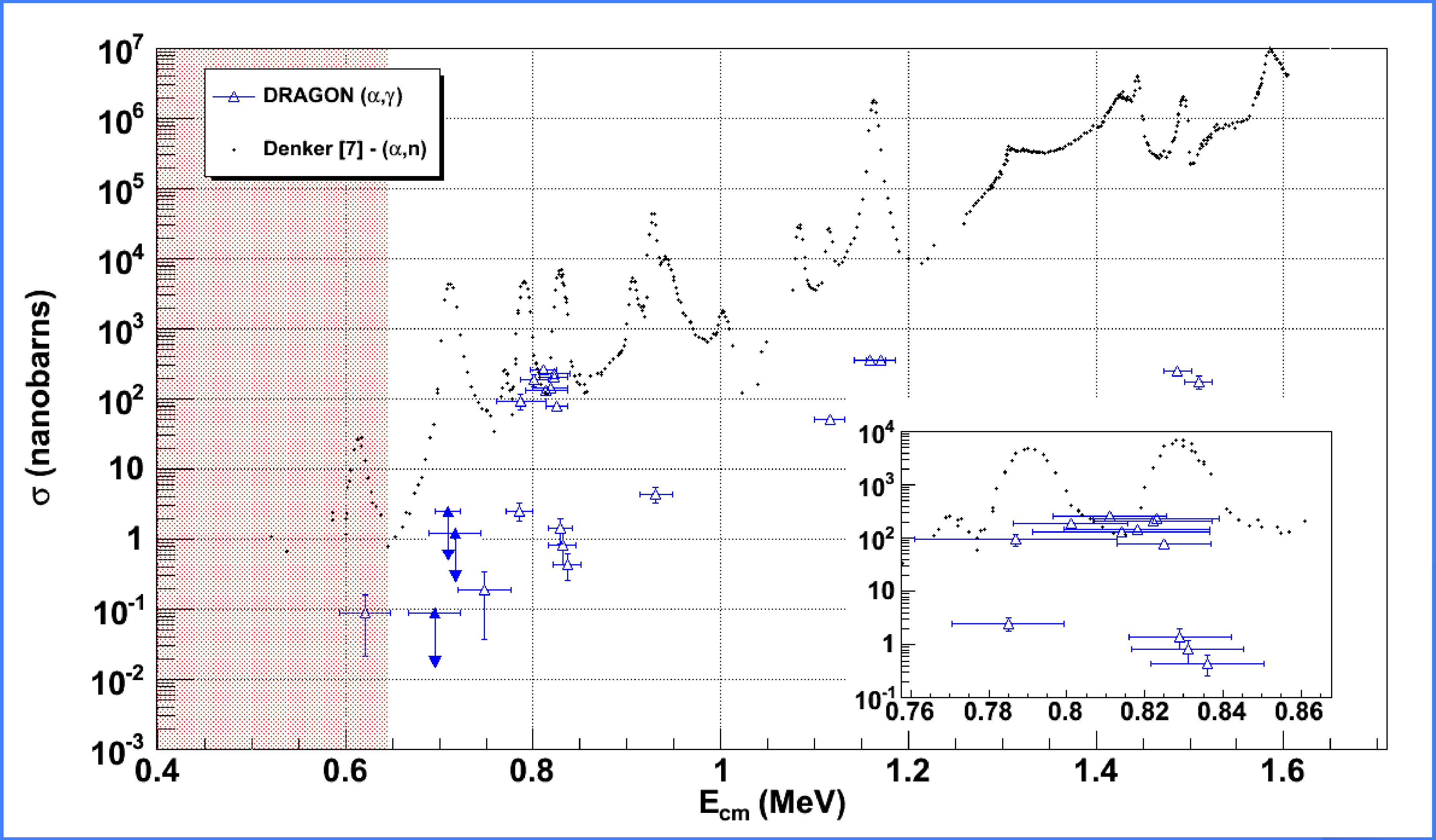


Hirschi et al, NIC-X 083 (2008)

Perform a direct measurement of the $^{17}O(\alpha,\gamma)$ reaction using DRAGON spectrometer

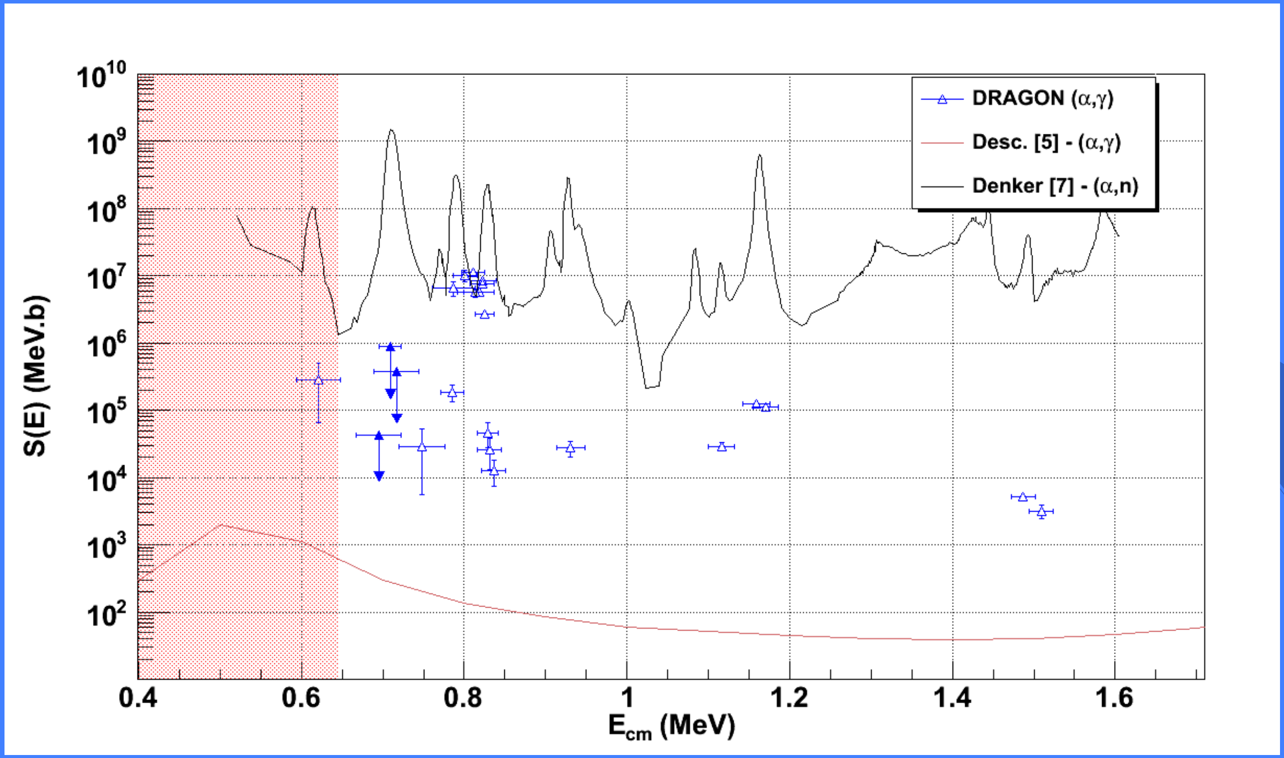
$^{17}O(a,\gamma)$ measurement – recoil selection in DRAGON





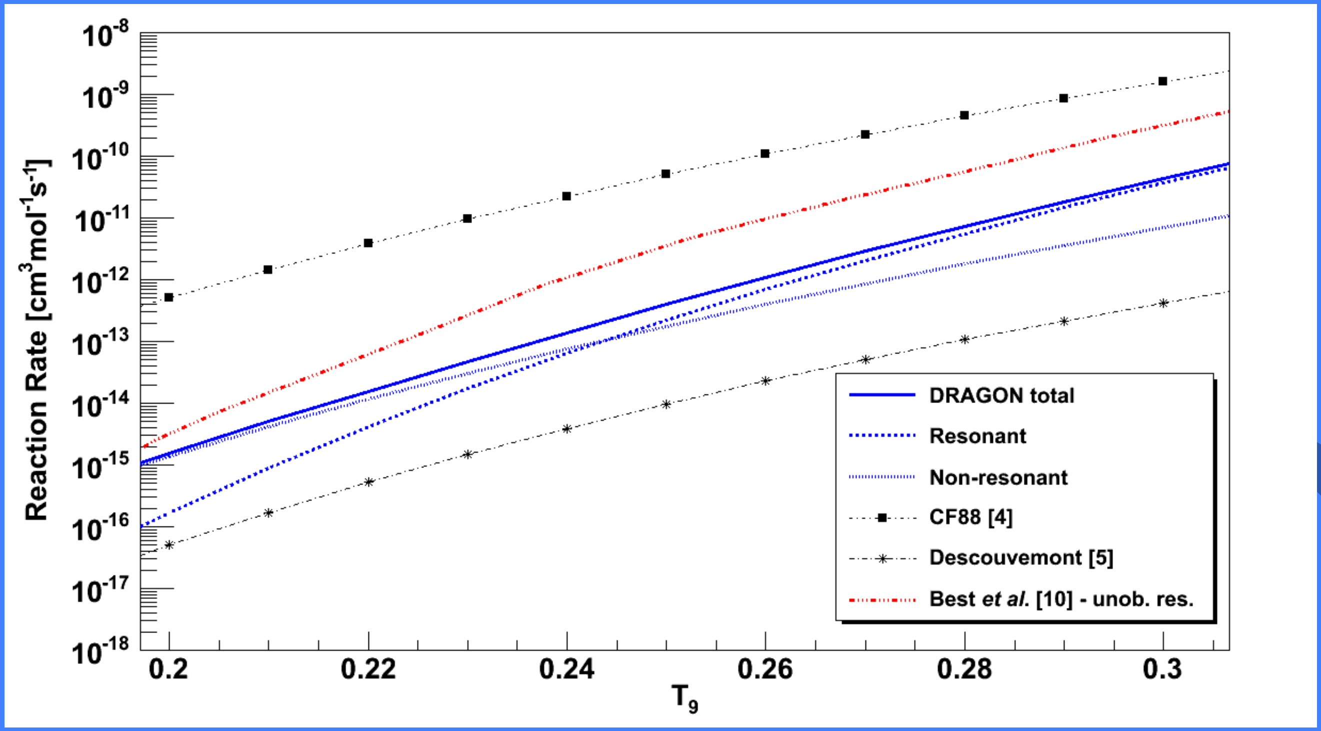
Preliminary data – submitted for publication

(α,γ) cross section is well below the previously measured (α,n)



Preliminary data – submitted for publication

This cross section gives an S-factor that excludes the prediction of Descouvement



Preliminary data – submitted for publication

Reaction rate from this measurement excludes the prediction of Descouvement but is still 100 times lower than CF (however this is an upper limit as have extrapolated)

However stellar model calculations show that the s-process abundances are not sensitive to the $^{17}O(\alpha,\gamma)^{21}Ne$ reaction rate if it is a factor of 100 lower, so there is still a significant production of s-process elements

So it appears Oxygen is not a poison in these stars

End with some acknowledgements

Much of the drive for this work has come from Alison Laird, Alex Murphy and Anuj Parikh

Collaborators on experiments

(p,α) - TRIUMF, Edinburgh (analysis by York student Clare Beer)
(p,γ) – TRIUMF, Edinburgh, CSM, MSU, ORNL (analysis by York student Charlie Ackers)
$^{19}F(^{3}He,t)^{19}Ne$ and $^{20}Ne(d,t)^{19}Ne$ – Barcelona, Edinburgh, TUM, McMaster, NSCL
(analysis by York student Philip Adsley)
$^{17}O(\alpha,\gamma)$ – TRIUMF, Edinburgh (analysis by York student Matt Taggart)