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

- $^{22}\text{Na}$ production in novae
- $^{18}\text{F}$ production in novae
- $^{16}\text{O}$ 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.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Decay Time</th>
<th>keV</th>
<th>Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{13}\text{N}$</td>
<td>862s</td>
<td>511keV</td>
<td>CO/ONe</td>
</tr>
<tr>
<td>$^{18}\text{F}$</td>
<td>158m</td>
<td>511keV</td>
<td>CO/ONe</td>
</tr>
<tr>
<td>$^{7}\text{Be}$</td>
<td>77d</td>
<td>478keV</td>
<td>CO</td>
</tr>
<tr>
<td>$^{22}\text{Na}$</td>
<td>3.75yr</td>
<td>1275keV</td>
<td>ONe</td>
</tr>
<tr>
<td>$^{26}\text{Al}$</td>
<td>1Myr</td>
<td>1809keV</td>
<td>ONe</td>
</tr>
</tbody>
</table>
Gammas emitted by long lived radioactive nuclei

MODEL 3

$T_{\text{max}} = 2.19 \times 10^6 \text{ K}$

$\rho = 2.28 \times 10^2 \text{ g cm}^{-3}$

$\varepsilon_{\text{max}} = 2.74 \times 10^{15} \text{ erg g}^{-1} \text{ s}^{-1}$

$\Delta M_{\text{max}} = 3.18 \times 10^{-5} M_{\odot}$

$^{26}\text{Al}$

$^{22}\text{Na}$

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

This will provide a stringent test on models, especially of Novae
COMPTEL measurements of $^{22}\text{Na}$ 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 $6.3 \times 10^{-9}$ solar mass of $^{22}\text{Na}$

$T_{1/2} = 3.75 \text{ yr}$

$E_\gamma = 1.275 \text{ MeV}$

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

**Key reactions:**

$^{21}$Na+p $\rightarrow$ $^{22}$Mg+$\gamma$  
(increased production)

$^{22}$Na+p $\rightarrow$ $^{23}$Mg+$\gamma$  
(decreased production)
Measuring the cross section

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

Production reaction

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

Beam of $^{21}\text{Na}$
Target of Hydrogen

Need to detect either the $\gamma$-rays or the recoiling $^{22}\text{Mg}$
..or both
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.

Cross section is larger than thought at low energies.
This time we calculate the rate rather than measure it.

\[
N_A < \sigma \nu > = 1.54 \cdot 10^{11} (\mu T_9)^{-3/2} \omega \gamma [\text{MeV}] e^{-11.605 E_p [\text{MeV}]} \frac{T_9}{\text{cm}^3} \frac{\text{s}}{\text{mole}}
\]

\[
\omega \gamma = \frac{2 J_R + 1}{(2 j_t + 1)(2 j_p + 1)} \frac{\Gamma_{p, \gamma}}{\Gamma_p + \Gamma_{\gamma}}
\]

For \( \Gamma_p \ll \Gamma_{\gamma} \):

\[
\omega \gamma = \omega \Gamma_p
\]

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

So do detailed spectroscopic study on \(^{23}\text{Mg}\)
Destruction reaction

“Brute Force” spectroscopy of $^{23}\text{Mg}$ using Gammasphere and the $^{12}\text{C}(^{12}\text{C},n)$ 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 $^{22}\text{Na}$
Feed through same Nova model gives factor of 3 less $^{22}\text{Na}$

So chances of observing a $^{22}\text{Na}$ signal from Nova from satellite missions may be considerably less that anticipated
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 6.528 MeV with $\Gamma_\gamma = 1.1 +/- 0.6$ eV

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

665 keV not been associated with any $^{19}$F analogue. Nesaraja assumed $\Gamma_\gamma = 1$ eV based on average of nearby states.
Direct measurement of $(p,\alpha)$ rate using $^{18}$F beam at TRIUMF on H target

TUDA Array

Array of segmented annular silicon detectors
$E_{\text{beam}} = 12.96 \text{ MeV}$

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

$E_\alpha$ 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
FIG. 3. The $^{18}\text{F}(\rho, \alpha)^{15}\text{O}$ $S$ 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 $^{18}\text{F}(\rho, \alpha)^{15}\text{O}$ $S$ 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?
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)
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.
As we looked closer at past data and analogue assignments we began to get worried.

So carry out high resolution measurement of \(^{19}\)F\(^{(3}\)He,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.
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 $^{20}\text{Ne}(d,t)^{19}\text{F}$
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 $^{16}\text{O}$ in the star can act as a neutron poison – n capture on the $^{16}\text{O}$ to form $^{17}\text{O}$ 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 $^{17}\text{O}$ can lead to two outcomes depending on ratio of the $^{17}\text{O}(\alpha,\gamma)$ and $^{17}\text{O}(\alpha,n)$ reaction rates:

- $^{17}\text{O}(\alpha,\gamma)$: neutron lost
- $^{17}\text{O}(\alpha,n)$: 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.

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

\(^{17}\text{O}(\alpha,n)\) measured, but still have \(10^4\) variation for \((\alpha,\gamma)\)

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

Hirschi et al, NIC-X 083 (2008)
$^{17}\text{O}(a,\gamma)$ measurement – recoil selection in DRAGON

November
Runs 20146-48, $E_{cm} = 0.823$ MeV

| hICsumMCPtof |  
|---|---|
| Entries | $1.974039e+07$ |
| Mean x | 437.5 |
| Mean y | 113.4 |
| RMS x | 71.92 |
| RMS y | 79.77 |
The DRAGON facility is designed to study radiative capture reactions relevant to nuclear astrophysics. It consists of a windowless recirculating gas target, surrounded by an ionization chamber (IC) and a two-stage electromagnetic recoil separator. A full description of the DRAGON separator is given in Hutcheon et al. [11] and Engel et al. [12].

The DRAGON recoil separator in the ISAC facility, experimentally, at energies between 0.6 and 0.8 MeV. These energies were determined from elastic scattering of the beam in the hydrogen in the gas target assembly. These elastic scattering events in the IC. The beam intensity was measured every hour in three Faraday cups (FC) located upstream of DRAGON, after the gas target and after the target, detected in two surface barrier detectors located by prompt gamma-rays detected in the BGO array in coincidence, the BGO array e- efficiency was determined from

At each energy, the raw yields were corrected for the cross sections for the reactions relevant to nuclear astrophysics. It consists of 4 anodes, providing the focal plane by an ionization chamber (IC). The IC measured the local time-of-flight (tof) of the reaction recoil energies. The IC e- efficiency, the charge state fraction for 4 O beam of typical intensity 600 enA impinged on the windowless gas target filled with helium. DRAGON targets e- efficiency of the ion chamber (IC) energy-tof graph, an example of which is shown in Fig. 3.

The separator e- efficiency, the charge state fraction for each of the reactions, was fitted using the empirical formula from [16]. This fit was used for the present work. The horizontal bars show the energy range between 0.8 and 1.6 MeV.

The horizontal bars show the energy range between 0.8 and 1.6 MeV. The first scanning the energy range between 0.8 and 1.6 MeV, focussing on regions of high expected yield as indicated by the Denker et al. [7] data. Subsequently a CM approximation was used.

Energy-tof graph, an example of which is shown in Fig. 4.

The (α,γ) cross section is well below the previously measured (α,n). The horizontal bars show the energy range between 0.8 and 1.6 MeV.
This cross section gives an S-factor that excludes the prediction of Descouvemement
Reaction rate from this measurement excludes the prediction of Descouvemont 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 $^{17}\text{O}({\alpha,\gamma})^{21}\text{Ne}$ 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\text{He},t)^{19}\text{Ne} and ^{20}\text{Ne}(d,t)^{19}\text{Ne} – Barcelona, Edinburgh, TUM, McMaster, NSCL
(analysis by York student Philip Adsley)
^{17}\text{O}(\alpha,\gamma) – TRIUMF, Edinburgh (analysis by York student Matt Taggart)