bottlenecks & waiting points in novae & x-ray burst nucleosynthesis

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nova and x-ray bursts are powered by hundreds to thousands of thermonuclear reactions on proton-rich unstable nuclei

Waiting Point Nuclei and Bottleneck Reactions can impact the element creation and energy generation in these explosions & should be identified for further study
we have devised the **first quantitative definition** of Waiting Points and Bottlenecks in the rp-process and put this into an **online tool** that anyone can use.

we have **verified** many Waiting Points and Bottlenecks in the literature and found **some new ones**; systematic calculations are underway.
the online tool, part of the Computational Infrastructure for Nuclear Astrophysics, would be useful to guide work on proton-rich nuclei such as

- measurements of masses, decay lifetimes, branching ratios
- measurements of capture cross sections
- theoretical calculation of structure & reactions of dripline nuclei
motivation – novae, x-ray bursts, & unstable nuclei

- reactions on proton-rich unstable nuclei power novae & x-ray bursts

- rates of these reactions are crucial inputs into simulations of these explosions, influencing element creation & energy generation … and almost all unmeasured

- which reactions – of the 100s or 1000s – should be measured with RIBs?
  - use sensitivity studies (change individual rates, examine changes in model predications)
  - use Monte Carlo studies (change all rates simultaneously, run 1000s of trials, examine correlations)

• consider “special” nuclei and reactions – Waiting Points and Bottlenecks
waiting points: nuclear species that happen to “collect” material – FLOW goes in quickly but out slowly

X-ray burst nucleosynthesis

succession of waiting points at long-lived nuclei with low (p,γ) rates
(peak Temperature 2 GK)

Abundance vs. Time

<table>
<thead>
<tr>
<th>Species</th>
<th>Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ni56</td>
<td></td>
</tr>
<tr>
<td>Ge64</td>
<td></td>
</tr>
<tr>
<td>Se68</td>
<td></td>
</tr>
<tr>
<td>Kr72</td>
<td></td>
</tr>
<tr>
<td>Sr76</td>
<td></td>
</tr>
<tr>
<td>Zr80</td>
<td></td>
</tr>
</tbody>
</table>

Time (sec)
Waiting points: nuclear species that happen to “collect” material – FLOW goes in quickly but out slowly.

If flow goes out faster, no more collection of material, and many abundances changed.

How do we FIND waiting points for further theoretical & experimental studies?
many discussions of waiting points in the literature, but NO quantitative definition
waiting points - definition

devise a **quantitative definition** of waiting point nuclei

each property we considered has some drawbacks

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Motivation</th>
<th>Exceptions and Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q$-value for $(p, \gamma)$</td>
<td>Low $Q$-value usually means suppressed $(p, \gamma)$ capture rate</td>
<td>$Q$-value does not always track with rate, especially as temperatures vary widely during explosion</td>
</tr>
<tr>
<td>Reaction rate</td>
<td>Suppressed destruction reactions suggest a possible waiting point</td>
<td>Does not account for total rate of destruction which depends on reaction rate and abundance</td>
</tr>
<tr>
<td>$\beta^+$ decay lifetime</td>
<td>Long decay lifetime suggests a possible waiting point</td>
<td>Other reactions such as $(p, \gamma)$ and $(\alpha, p)$ may destroy this nucleus</td>
</tr>
<tr>
<td>Destruction lifetime</td>
<td>Long lifetime suggests a possible waiting point</td>
<td>This tracks better than decay lifetime and also works for stable nuclei</td>
</tr>
<tr>
<td>abundance</td>
<td>Having a large abundance that increases suggests a waiting point</td>
<td>More flow may pass through neighboring nuclei and give them higher abundances</td>
</tr>
<tr>
<td>Reaction flux</td>
<td>Flux into nuclei should be larger than flux out</td>
<td>Better measure than reaction rate; can depend sensitively on time interval</td>
</tr>
</tbody>
</table>

we **COMBINE** these properties to come up with a good way to find waiting points
run an element synthesis calculation, store the abundance vs. time and reaction flux vs. time information

choose a **TIME INTERVAL**

examine each nucleus & compare to its neighbors in the N-Z plane
waiting points – search procedure

REJECT nuclei with

- short destruction lifetime \( [<0.2 \text{ sec}] \)
- low abundance \( [<10^{-6}] \)
- peak Flux out $>$ peak Flux in
- negative total integrated flux [net flux is negative, abundance is decreasing]
ACCEPT nuclei with
reasonably large total integrated Flux \([ > 10^{-4} ]\)
AND reasonably long lifetime \([ > 1 \text{ sec}]\)

REPEAT the test for all nuclei in the simulation
• **test algorithm** on a series of simulations

  verify that every waiting point found by procedure meets our criteria

  verify that there are no other waiting points missed by procedure

• try to **reproduce some known waiting points** from the literature

• change input rates in simulation to “create” a new waiting point or “destroy” an existing one – verify that our procedure works
Computational infrastructure for nuclear astrophysics

Available at nucaastrodata.org

Users in 70 institutions in 20 countries

Online system can determine the astrophysical impact of
• what we already measured
• what we propose to measure next
quickly perform searches for waiting points with custom parameters
online software tool – waiting point finder

Please enter criteria for determination of waiting points in the fields below.

- Min abundance: 1.0E-6
- Min effective lifetime (lifetime against destruction): 0.2
- Min ratio of effective lifetime to beta lifetime: 0.5

quickly perform searches for waiting points with custom parameters
quickly perform searches for waiting points with custom parameters
waiting points displayed with abundances or reaction flux

quickly perform searches for waiting points with custom parameters
bottlenecks

All reaction FLOW passes through these reactions.

If a bottleneck reaction is turned off, result is a "Thermonuclear Traffic Jam".

How do we define & find bottlenecks?
bottlenecks – definition

consider all reactions that produce nuclei with mass greater than or equal to A
**bottlenecks – search procedure**

**REJECT** presence of bottleneck if

- all reaction fluxes too low \[ < 10^{-12} \] relative to largest flux in simulation
- OR two or more fluxes are too high \[ > 10^{-6} \] relative to largest flux
**bottlenecks – search procedure**

REJECT presence of bottleneck if

all reaction fluxes too low [ < $10^{-12}$ ] relative to largest flux in simulation

OR two or more fluxes are too high [ > $10^{-6}$ ] relative to largest flux

ACCEPT presence of bottleneck if

only ONE FLUX is high [ > $10^{-6}$ ] AND all other fluxes much lower [ factor $10^{-4}$ down]

REPEAT for all mass values in the simulation
online software tool – bottleneck finder

quickly perform searches for bottlenecks with custom parameters
quickly perform searches for bottlenecks with custom parameters
online software tool – bottleneck finder

Below is a list of reactions that are bottlenecks for the synthesis of nuclei with masses greater than or equal to the Bottleneck Mass. Click Submit Bottleneck Reactions to visualize these results with the Animator. Click Close Bottleneck Reaction Finder to close the Bottleneck Reaction Finder and not submit the results. Check View Detailed Report to view the user input as well as the output of the Finder.

Bottleneck Reaction Finder Report:

<table>
<thead>
<tr>
<th>Bottleneck Mass</th>
<th>Reaction</th>
<th>Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>$^{12}$C $\rightarrow$ $^{13}$N</td>
<td>Major Bottleneck</td>
</tr>
<tr>
<td>64</td>
<td>$^{63}$Ga $\rightarrow$ $^{64}$Ge</td>
<td>Major Bottleneck</td>
</tr>
<tr>
<td>68</td>
<td>$^{67}$As $\rightarrow$ $^{68}$Se</td>
<td>Major Bottleneck</td>
</tr>
<tr>
<td>72</td>
<td>$^{71}$Br $\rightarrow$ $^{72}$Kr</td>
<td>Major Bottleneck</td>
</tr>
</tbody>
</table>

quickly perform searches for bottlenecks with custom parameters
bottlenecks displayed with abundances or reaction flux

quickly perform searches for bottlenecks with custom parameters
Nova - Hot Inner Zone
Peak Temp 0.4 GK
1 sec after peak
flux plot

Flux Legend
- $10^0 - 10^{-1}$
- $10^{-1} - 10^{-2}$
- $10^{-2} - 10^{-3}$
- $10^{-3} - 10^{-4}$
- $10^{-4} - 10^{-5}$

Waiting points:
- $^{14}\text{O}$, $^{15}\text{O}$, $^{19}\text{Ne}$
- $^{23}\text{Mg}$, $^{31}\text{S}$, $^{32}\text{S}$
**X-ray burst**

**Peak Temperature 2 GK**

**Waiting Points near peak:**
- $^{64}\text{Ge}$, $^{72}\text{Kr}$, $^{75,76}\text{Sr}$

**Bottlenecks near peak:**
- $^{12}\text{C}(p,\gamma)^{13}\text{N}$, $^{71}\text{Br}(p,\gamma)^{72}\text{Kr}$
- $^{75}\text{Rb}(p,\gamma)^{76}\text{Sr}$, $^{79}\text{Y}(p,\gamma)^{80}\text{Zr}$

**Result:** Find known waiting points and some new ones …
X-ray burst
Peak Temperature 2 GK

Bottlenecks 40 sec after peak:
$^{12}$C(p,γ)$^{13}$N, $^{37}$K(p,γ)$^{38}$Ca, $^{41}$Sc(p,γ)$^{42}$Ti,
$^{44,45}$V(p,γ)$^{45,46}$Cr, $^{49}$Mn(p,γ)$^{50}$Fe,
$^{58}$Cu(p,γ)$^{45,46}$Zn, $^{71}$Br(p,γ)$^{72}$Kr,
$^{75}$Rb(p,γ)$^{76}$Sr, $^{79,80}$Y(p,γ)$^{80,81}$Zr,
$^{84}$Nb(p,γ)$^{85}$Mo, $^{87}$Tc(p,γ)$^{88}$Ru,
$^{92}$Rh(p,γ)$^{93}$Pd, $^{95}$Ag(p,γ)$^{96}$Cd

Waiting Points 40 sec after peak:
$^{72}$Kr, $^{75,76}$Sr, $^{79,80,81}$Zr, $^{84}$Mo, $^{88}$Ru, $^{92}$Pd
**future**

**systematic searches** of nova & x-ray burst simulations for Bottlenecks & Waiting Points – determine dependence on astrophysical model, search parameters, time window

device more elaborate criteria to **RANK** waiting points and bottlenecks

device tools to **search for other “special” nuclei** and reactions in rp-process burning
Waiting Point Nuclei and Bottleneck Reactions can impact the element creation and light curve of novae & x-ray bursts

we have quantitatively defined these concepts & built an online tool to find them

we used our tool to verify numerous waiting points / bottlenecks & find some new ones