Studying the \((\alpha, p)\)-process in X-Ray Bursts using Radioactive Ion Beams

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Neutron stars: 1.4 $M_\odot$, 10 km radius

Type I X-Ray Bursts (XRBs)

Accretion rate $\sim 10^{-8}/10^{-10} M_\odot$/year
Peak x-ray burst temperature $\sim 1.5$ GK
Recurrence rate $\sim$ hours to days
Burst duration of 10 – 100 s
Observed x-ray outburst $\sim 10^{39} – 10^{49}$ ergs

Nucleosynthesis in XRBs

- **Triple-\(\alpha\) process to form \(^{12}\text{C}\)**
- **Rapid proton-capture process (\(rp\) – process)**
  - Series of \((p,\gamma)\) reactions and \(\beta^+\) – decays
- **\((\alpha,p)\) – process**
  - Sequence of \((\alpha,p)\) and \((p,\gamma)\) reactions
- Reach nuclei far from stability, close to the proton-drip line
Waiting points in XRBs

  - $^{22}\text{Mg}$
  - $^{26}\text{Si}$
  - $^{30}\text{S}$
  - $^{34}\text{Ar}$

- At lower temperatures, nuclei with low $(p,\gamma)$ Q values come into $(p,\gamma)$ – $(\gamma,p)$ equilibrium

- If the $(\alpha,p)$ reaction rate is weak OR if the temperature is too low to overcome the Coulomb barrier for the $(\alpha, p)$ process, nuclear flow must await $\beta^-$ decay ($T_{1/2} = \text{few seconds}$) before continuing on
Waiting Point Effects

- Waiting points can affect the nucleosynthetic path
  - Final elemental abundances
  - Energy output during burst
  - Composition of neutron star surface → affects observables

- Luminosity profile can be affected due to pause in energy output as process pauses at waiting point
  - Leads to observed double-peak luminosity profiles

Table 19. Summary of the most influential nuclear processes, as collected from Tables 1–10. These reactions affect the yields of at least one isotope when their nominal rates are varied by a factor of 10 up and/or down. See text for details.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Models affected</th>
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<tbody>
<tr>
<td>$^{28}$O($p$, $p$)$^{28}$Ne</td>
<td>K04-B3, K04-B4, K04-B6</td>
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Reaction Rates in XRBs

- Current models and studies are based on theoretical Hauser–Feschbach reaction rates → **Almost no experimentally obtained information is known**
  - NIC_XI_366, NIC_XI_098

- Given the current limitations of radioactive beam facilities most $r\!p$– and $\alpha$, $p$–process reactions are inaccessible

- Radioactive beams close to stability can be produced at ATLAS via the “in-flight” technique

- Studied $(\alpha,p)$ reactions on potential waiting points using time-inverse and inverse kinematic reactions:
  - $p(^{29}\text{P},^{26}\text{Si})\alpha$
  - $p(^{33}\text{Cl},^{30}\text{S})\alpha$
  - $p(^{37}\text{K},^{34}\text{Ar})\alpha$
Experimental Setup

- Beams produced by ATLAS
  - Stable beam produced in ECR source and accelerated
  - **Radioactive ion beam (RIB)** produced via “in-flight” technique

- RIB enters target chamber
  - Slowed by Au degrader foils
  - Incident on CH\(_2\) target

- Reaction products detected in coincidence
  - \(\alpha\)-particles detected in Double-Sided Si Detector (DSSD)
  - Heavier reaction products separated by Enge SplitPole Spectrograph used in gas–filled mode and detected in Parallel Grid Avalanche Counter (PGAC) and ionization chamber at focal plane of spectrograph
“In-Flight” Technique

- Examples: $^6$He, $^7$Be, $^8$Be, $^8$Li, $^{11}$C, $^{14}$O, $^{16}$N, $^{17}$F, $^{20,21}$Na, $^{25}$Al, $^{29}$P, $^{33}$Cl, and $^{37}$K
- $^{32}$S$^{13+}$ stable primary beam
- Gas cell filled with deuterium
- $^{32}$S(d,n)$^{33}$Cl produces $^{33}$Cl$^{17+}$ radioactive beam
33Cl beam production

- Resulting beam is a cocktail of $^{32}\text{S}^{13+}$, $^{32}\text{S}^{14+}$, $^{32}\text{S}^{15+}$, $^{32}\text{S}^{16+}$, and $^{33}\text{Cl}^{17+}$

- $^{33}\text{Cl}^{17+}$ Tuned with $\Delta E$ – $E$ telescope
  - Si Surface Barrier (SSB) detectors
    - $\Delta E$ 20 µm thick
    - $E$ 150 µm thick

- RF sweeper is used to eliminate much of the contaminant $^{32}\text{S}$ beam

- Final $^{33}\text{Cl}$ beam intensity of $1.67 \times 10^4$ pps
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Proof of Principle with stable beam reactions: 

\[ p(^{33}\text{S}, ^{30}\text{P})\alpha \]

- Using the same setup the \( p(^{33}\text{S}, ^{30}\text{P})\alpha \) reaction was studied with a stable \(^{33}\text{S}\) beam
- Gating on the \(^{30}\text{P} - \alpha\) coincidences and particle groups gives clear kinematic curves
- Data shown for multiple energy points
- Blue curves represent kinematic simulations
\( p({}^{33}\text{Cl}, {}^{30}\text{S})\alpha \) Data

- \( {}^{30}\text{S} \) – \( \alpha \) coincidences seen as well defined timing peak
- Using radioactive \( {}^{33}\text{Cl} \) beam, particle ID is more difficult due to diffuseness of beam
$^p(^{33}\text{Cl},^{30}\text{S})\alpha$ Results: Simulations vs. Experiment
$p(^{33}\text{Cl},^{30}\text{S})_\alpha$ Results

- Normalized via
  - Rutherford scattering
  - Direct beam measurements in spectrograph
  - Two methods agree within 10%

- Measurements made at three different energy points

- NON-SMOKER code give cross sections based on Hauser-Feshbach models (similar to those used in models where experimental information is not available)

- Measurements at lower energies are needed for x-ray burst models
$p(^{37}\text{K}, ^{34}\text{Ar})_\alpha$ Results (PRELIMINARY)
$^{29}\text{P}$ beam development and preliminary $p(^{29}\text{P},^{26}\text{Si})\alpha$ run (June 2010)
Summary and Future Plans

- $^{30}\text{S}(\alpha,p)^{33}\text{Cl}$ reaction rate affects
  - nucleosynthesis in XRBs
  - the energy output of XRBs
  - the luminosity of double-peaked XRBs

- $^{34}\text{Ar}(\alpha,p)^{37}\text{K}$ and $^{26}\text{Si}(\alpha,p)^{29}\text{P}$ is also a possible waiting point that may affect the double-peaked structure of luminosity profiles

- Radioactive $^{29}\text{P}$, $^{33}\text{Cl}$ and $^{37}\text{K}$ beams have been produced at ATLAS

- Inverse kinematic studies of $(\alpha,p)$ reactions has been successfully completed using the Enge SplitPole Spectrograph and cross sections for three energy points have been measured for the $^{30}\text{S}(\alpha,p)^{33}\text{Cl}$ and $^{34}\text{Ar}(\alpha,p)^{37}\text{K}$ reactions; One energy point for the $^{26}\text{Si}(\alpha,p)^{29}\text{P}$ reaction, which is currently being studied

- More energy points, in the astrophysical range, should be measured in the future

- Measurements of other waiting point nuclei $^{22}\text{Mg}$

- Direct $(\alpha,p)$ measurements using HELIOS with a gas target...?
Thank You!!

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