Light element reactions and fission in the r-process

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Abstract

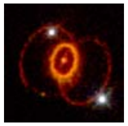
The r-process is thought to be a primary process because of observed universal abundance distribution. Light element reactions that form seed elements are important for primary r-processes because of such reactions' effect on the neutron-to-seed ratio at the beginning of r-process. We studied the effect of neutron-capture on light elements and the new reaction flow $^4He(^2n,\gamma)^6He(\alpha,n)^9Be$ for three different environments. Both effects have been neglected for r-process studies. We found neutron-capture on light elements is significant in all environments. Since neutron-capture rates of such light elements have large uncertainties, more reliable rates for those reactions are needed. Although $^4He(^2n,\gamma)^6He(\alpha,n)^9Be$ flow does not affect high entropy models. it should be considered for r-processes in low entropy, low temperature models.

Astrophysical site for the r-process

The r-process is the rapid neutron-capture process which probably occurred in explosive events such as Type II supernovae or neutron star mergers. However, despite of decades of study, the astrophysical site for the r-process is still unknown.
The possible candidates can be categorized following three types;

- Neutrino-driven winds in Type II supernovae
 (e.g., Woosley et al. 1996, Otsuki et al. 2001)

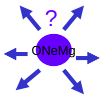
The hot proto-neutron stars release neutrino during its Kelvin-Helmholtz cooling phase. Those neutrino heat up the material on the surface and blow them off.


SN1987A

Typical entropy is about 400, electron fraction is about 0.4. Background neutrinos also play important role for r-process.
This environment is also expected to occur in GRBs.

<Main Objection>
Entropy problem (Can such high entropy be realized?)
Neutrino problem (Neutrino increase Y_e.)

- Prompt explosion of low mass supernovae
 (e.g., Wheeler et al. 1998, Wanajo et al. 2003)



Intermediate mass stars (8~12$M_\odot$)
could explode as prompt supernovae.
Typical entropy is about 15, electron fraction is about 0.2.

<Main Objection>
explosion mechanism (Does it really explode?)
over production of r-process elements

- Neutron star mergers
 (e.g. Freiburghaus et al. 1999)

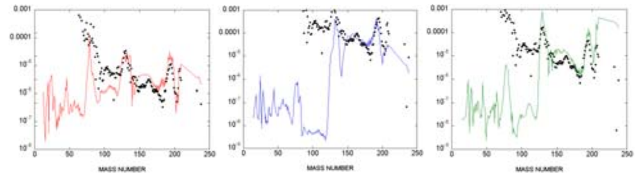
Merger of neutron-star binary can generate extremely neutron-rich environments.
The entropy is very low, but electron fraction is low Ye<0.2.

<Main Objection>
Timescale of neutron star merger
Event rate

Theoretical calculation

dynamical network code
seed production + r-process
More than 3000 isotopes

Examples of our calculations



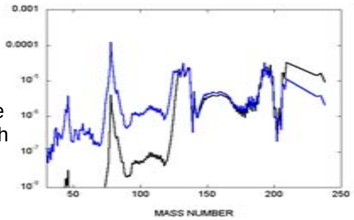
Neutrino-driven wind | Low mass SNe | Neutron star mergers

Neutron-capture of light elements Z<10

The importance of neutron-capture of light elements for r-process in neutrino-driven winds has been pointed out by Terasawa et al. (2000). We studied the effect of those reactions on r-process in different environments.

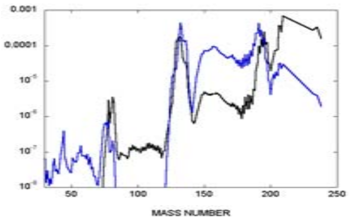
- Neutrino-driven winds

The result with neutron-capture of light elements shows less actinide elements and more 2nd peak elements. For each results, the blue lines indicate the final abundances of calculation with neutron-capture of light elements, the black lines are calculation without those reactions.



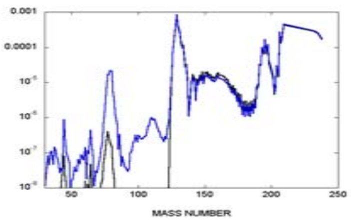
- Low mass supernovae

The result with those reactions shows less actinide elements and more 2nd peak and 3rd peak elements.



- Neutron star mergers

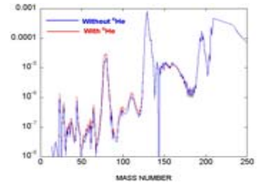
Effects of neutron-capture on light elements on abundance of elements lighter than 2nd peak. There is no significant difference for A>130. This is probably because the fission cycle covered up the difference from light elements reactions.



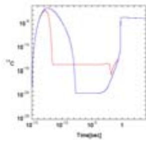
Neutron-capture of light elements plays an important role for the r-process in all candidates. Since those reactions consume free neutrons, final actinide abundances become smaller. For low mass supernovae model, our calculation cannot make enough actinide elements to reproduce observed abundance when we include those reactions.
If we assume all the nuclear physics which has been adopted in our calculation is reasonable, low mass supernovae model should be discarded. More reliable reaction rates for neutron-capture of light elements are necessary for further discussion.

Di-neutron capture of ^4He

We studied the effect of the new reaction flow
$^4He(^2n,\gamma)^6He(\alpha,n)^9Be$.
The effect of this new reaction flow is not significant for the r-process in neutrino-driven winds nor low mass supernovae. However, the effect of this flow is significant for neutron star merger models.
This reaction flow could be important for the r-process in low S, low T environments.

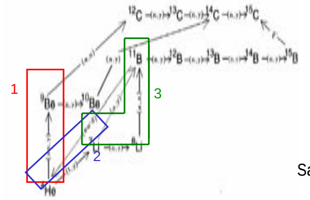


Final abundances of calculation with (Red line) and without (Blue line) 4He(2n, g)6He(a,n)9Be flow.



Time variation of 12C abundances. Although the difference of final abundances is small, there are clear differences at the early stage of nucleosynthesis.

Identified important reaction flow



Sasaqui et al. 2005

The role of fission

In our calculations of r-process in neutron star mergers, the difference of light element reactions does not appear final abundances for A>130. This is because the fission cycle covered the difference at the early stage of nucleosynthesis in this most neutron-rich model. Further studies of such dominant fission cycles could help to understand the observed universal abundance distribution.
In addition to this, the fission determines the endpoint of r-process and mass distributions of fission fragments effects on final abundance distribution. The former is important when suitable conditions for the r-process are discussed. The latter could be related to observed excesses of light neutron-capture elements. The reliable fission model is necessary for studies to identify astrophysical sites for the r-process(es). Theoretical studies of the effects of fission on the r-process are now ongoing.

<References>
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