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碩士論文

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Master Thesis

紊流混合對快中子捕獲過程(r-process)核合成的影響

Effect of turbulence mixing on R-process nucleosynthesis

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摘要

2017 年 8 月雙中子星合併 (BNSM) 事件 GW170817 的重力波和電磁輻射的觀測，不僅標誌著重力波多信使天文學的開始，也提供了不少的證據——證實雙中子星合併是由快中子補獲過程 (r-process 或 快過程) 的不穩定核衰變，來爲短 γ 射線暴 (sGRB) 和千新星提供能量。

最近的研究顯示，諸如短 γ 射線暴噴流穿透雙中子星合併之噴出物的機制，可能會導致噴出物內部大規模的紊流。這種紊流可能會導致噴出物中不同成分，且可能具有不同的核合成條件的流體混合。如果紊流引起的混合發生在快過程期間，與沒有混合的情況相比，它可能會影響快過程的最終產物。

在本論文中，我們使用一個簡單的雙流體簡單模型來探討成分混合對雙中子星合併事件中，快過程核合成結果的潛在影響。而我們發現不僅混合本身會改變最終結果，而且混合發生的時間點也會使結果具有不同的狀況。

特別是我們發現，如果當其中一流體處在快過程中，而另一種流體已完成其快過程時發生混合，混合效應會導致後者的自由中子的突然增加。因此，它可以幫助在快過程已停止的流體重新啓動快過程；與兩種未混合流體的直接平均值相比，這使得整個系統整體得以生成更重的核素。 另一方面，如果當兩種流體仍在快過程中時發生混合，則混合讓兩流體交換其剩餘的自由中子，使高 Y_e 流體獲得更多自由中子進行快過程，而低 Y_e流體獲得較少的自由中子進行快過程。這將導致兩種流體的最終元素分布彼此接近，並且與在混合系統剛開始時取部分初始 Y_e 平均值非常相似。

關鍵字— 快過程核合成，紊流，中子星合併，短Gamma射線爆(sGRB)。

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Abstract

The detection of the gravitational wave and electromagnetic emissions from the binary neutron star merger (BNSM) event GW170817 in August 2017 not only marked the beginning of the gravitational-wave multi-messenger astronomy, but also provided evidence that BNSMs are the sources of the short gamma-ray bursts (sGRB) and kilonovae – transients powered by the decay of unstable nuclei synthesis by the rapid neutron-capture process (r-process).

Recent studies suggested that mechanisms such as the sGRB jet penetrating the BNSM ejecta may result in large-scale turbulence inside the ejecta. Such turbulence can possibly cause composition mixing of different fluid components inside the ejecta, which might have different nucleosynthesis conditions. If the mixing caused by the turbulence happens during r-process, it may affect the resulting r-process yield predictions when compared to cases without mixing.

In this thesis, we use a simple two-fluid toy-model to study the impact of a potential composition mixing on the r-process nucleosynthesis outcome in BNSM events. We find that not only mixing itself will alter the final result, but also the time that mixing happen will make the result have different shape.

In particular, we find that if mixings happen when one of fluids is within the r-process while the other one has finished its r-process, mixing effect leads to sudden increase of free neutrons in the latter. Thus, it can help re-start the r-process in the fluid wherein the r-process had ceased. This allows the whole system to produce overall heavier nuclei when compared to the direct average of two unmixed fluids. On the other hand, if mixings occur when both fluids are still within the r-process, then mixing let both fluids exchange their remaining free neutrons, make high Y_e fluid get more free neutron to r-process, and low Y_e fluid get lesser free neutron to r-process, where $Y_e \equiv n_e/n_b$, and n_e (n_b) is the electron (baryon) number density. This will cause both fluids' final abundance distribution getting close toward each other, and it pretty similar to take a partial initial Y_e averaging at begin of mixing system.

Keywords— r-process nucleosynthesis, turbulence, neutron stars mergers(NSM), short gamma-ray burst(sGRB).

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Chapter 1

Introduction

A few years ago, the gravitational wave and electromagnetic emissions from the binary neutron star merger (BNSM) event GW170817 were observed [Abbott et al., 2017b, Abbott et al., 2017a]. This event not only marks an important milestone of observational astronomy, but it also provides valuable understanding of short gamma-ray bursts (sGRB) and kilonovae. In particular, by analyzing the lightcurve and spectra evolution of the GW170817 kilonova, it provides the first direct evidence that the rapid neutron-capture process(r-process), which is responsible for the production of a half of nature's heavy elements, operate inside the ejecta of BNSM [Cowan et al., 2021].

The r-process is a primary nucleosynthesis method, which can produce heavy elements through a series of neutron capture and β-decay. For an r-process to operate in an expanding ejecta, it requires that the neutron capture rate averaged over all nuclei being much larger than the corresponding averaged beta-decay rate. Thus, it demands a neutron-rich environment with a large neutron-to-seed ratio, $R_{n/s} \equiv n_n/n_s \gg 1$, where n_n is the neutron number density and n_s is the seed nuclei[1] number density.

When r-process proceeds, neutrons are consumed to synthesize heavier nuclei. This cause $R_{n/s}$ to decrease. Eventually, r-process freezes out when $R_{n/s}$ drops

[1]Generally, seed nuclei include all nuclei heavier than the iron group.

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roughly below 1 and the averaged beta-decay rate exceeds the averaged neutron-capture rate [Cowan et al., 2021]. So, we can say when n/s = 1, r-process is mostly ended.

In general situation, r-process timescale is less than $\mathcal{O}(1)$ s, and the exact duration sensitively depends on astrophysical conditions such as the electron fraction Y_e. Different ejecta from the different BNSMs will also have different r-process conditions. The impact of these astrophysical uncertainties as well as the uncertainties from the yet-unknown properties of very neutron-rich nuclei require further efforts to robustly predict the nucleosynthesis yields from BNSMs [Cowan et al., 2021].

One very interesting aspect that has not yet been addressed in literature, is the effect of interaction of the sGRB jet and BNSM ejecta on r-process outcome. Recent studies suggested that as sGRB jet penetrating the BNSM ejecta, it may cause large-scale turbulence inside the outgoing ejecta, and such turbulence can causing composition exchange between non-identical nearby fluids in the ejecta [Hamidani et al., 2019, Hamidani and Ioka, 2020].

Since the timescale for the jet penetrate the ejecta is around 1 to 5 seconds [Hamidani et al., 2019, Hamidani and Ioka, 2020], similar to the r-process timescale. Any composition mixing caused by turbulence during the r-process may alter the r-process condition and affect the predicted r-process outcome.

In this thesis, we set up a very simple two-fluid toy model to explore the potential impact of turbulence mixing on the outcome of the r-process nucleosynthesis. The thesis will be divide into several parts :

- In chapter 2, we define the relevant parameters in our simple model and describe how we implement the mixing with existing r-process calculations without mixing.

- In chapter 3, we begin to discuss our toy model's simulation results. First, we start from analyzing single fluid's evolving results, to have a sense about how it be influence by initial conditions. Then we will continue to explore complete

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mixing and incomplete mixing, which have basic and advance mixing situation.

- In chapter 4, we conclude the work done in this thesis and discuss future perspectives.

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Chapter 2

Physical Model

To investigate the impact of mixing on r-process nucleosynthsis, we adopt a toy model as follows. We describe a system consisting of the two fluid elements, each of which has its own initial electron number fraction Y_e. For simplicity, we assume that both of them have the same expansion property represent by a parameterized trajectory(see sec 2.2). For the mixing that can cause composition exchanged between the two fluids, we model this with three parameters :

1. mixing process's duration T_d
2. the final fraction of composition exchange after all mixing F_m
3. times of mixing N_m

Below in sec 2.1, we describe how we select these parameters, and in sec 2.2, we describe how we implement the prescribed mixing process with our r-process nucleosynthesis simulation code.

2.1 Parameter set-up

To see how mixing events will causing differences in final elements distribution, we manually set up multiple combinations with different initial values and mixing conditions.

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2.1.1 Initial electron fraction selection Y_e

In our two fluids system, we select different Y_e combinations for our two-fluid system. According to previous studies, the Y_e distribution in merger ejecta correspond with the angle from jet penetrating [Domoto et al., 2021], in ejecta typically increase for ejecta with larger angles with respect to the axis perpendicular to the merging plane. The range of Y_e can vary from 0.01 to 0.5. Thus, we assume that each fluid in our toy model can have its Y_e from the following five values (1)Y_e=0.05 (2)Y_e=0.15 (3)Y_e=0.25 (4)Y_e=0.35 and (5)Y_e=0.45. Requiring that the two fluids have different Y_e, this leads to 10 different Y_e combinations.

2.1.2 The duration of mixing T_d

We use mixing duration T_d to present how long that jet take to penetrate ejecta, which also means how long the mixing can remain. Since the sGRB penetrating duration is typically less than 5s [Hamidani et al., 2019], we choose five of different T_d - (1)T_d=0.1s (2)T_d=0.32 (3)T_d=1.0s (4)T_d=1.7s and (5)T_d=3.2s. Note that the 1.7s one is related to realistic case GW170817 - its sGRB signature was captured about 1.7 seconds after the detection of gravitational waves, which might indicate that the jet produced in the core of merged binary neutron stars take around 1.7 seconds to break through the surrounding ejecta.

2.1.3 Mixing times N_m

In each calculation, assume that mixings can happen for N_m times that are separated uniformly within the duration T_d. So if we only mix 1 time during the whole duration, the exact mixing time will be the middle point of duration or half of T_d. If mixing 2 times, the exact mixing times will be one-third of T_d and two-third of T_d from start. For example. if T_d is 1 second, the $N_m = 1$ case will be 0.5 second, $N_m = 2$ will be 0.33 and 0.66 second.

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2.1.4 Exchanging efficiency with in mixing duration F_m,f_m

Here we present exchanging efficiency with "the exchanging percentage of fluids' composition", and we define mixing percentage in whole T_d duration(each mixing times) with $F_m(f_m)$. In this thesis we set 3 different "F_m" to compare differences between non-identical efficiency cases. Then we design the variable "f_m" will change with F_m and "mixing times N_m" as the correspondence of binomial expansion at (2.1) and (2.2).

$$1 - F_m/2 = \sum_{i=0,2,4...}^{m} C_i^m (f_m/2)^i (1 - f_m/2)^{m-i} \tag{2.1}$$

$$F_m/2 = \sum_{i=1,3,5...}^{m} C_i^m (f_m/2)^i (1 - f_m/2)^{m-i} \tag{2.2}$$

where (2.1) and (2.2) are in the new first(second) fluid, the remaining part of the first(second) fluid and the exchanged part from the second(first) fluid after several mixing. m is mixing times(relate to N_m), C is binomial coefficient from Pascal's triangle, and $1 - f_m/2$ is remaining fraction of current fluid in each mix.

For example, if we fixed "F_m" to 80%, then for mixing 1-time case the only mixing f_m will exchange 80%, but for mixing 2-times each f_m will need to exchange 55.3% to achieve "F_m"=80%. Notice that this ratio contains both fluids' exchanging parts, so for the current mix 80% case, at first mixing time each fluid are actual exchange 27.65%, and exchange with this percentage 2-times will result in 40% for each fluid as one duration.

The following table.1 will demonstrate how equation (2.1) and (2.2) work, with the parameter that we designed earlier.

To sum up these settings, it will be like a 4D array, but if we fix one of the variable, the 4D array will become a 3D array like a cube(Figure 2.1). For example, if we fix $F_m(N_m)$, the one axis of 3D cube is different initial Y_e setting, another one is mixing duration, and the other one is mixing times N_m(exchanging efficiency F_m).

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Table 2.1: The example of exchange configuration

This table shows how much each mixing time should exchange, to achieve the whole fluid's mixing setting. The top row is mixing times, left column is the total exchanging ratio in the system. For example, for mixing 80% with mixing thrice case, each mixing should exchange 41.5% to result in whole system exchange 80% by the end of mixing.

	$N_m = 1$	$N_m = 2$	$N_m = 3$	$N_m = 4$
$F_m = 50\%$	$f_m = 50\%$	$f_m = 29.28\%$	$f_m = 20.64\%$	$f_m = 15.92\%$
$F_m = 80\%$	$f_m = 80\%$	$f_m = 55.3\%$	$f_m = 41.5\%$	$f_m = 33.1\%$
$F_m = 100\%$	$f_m = 100\%$	$f_m = 100\%$	$f_m = 100\%$	$f_m = 100\%$

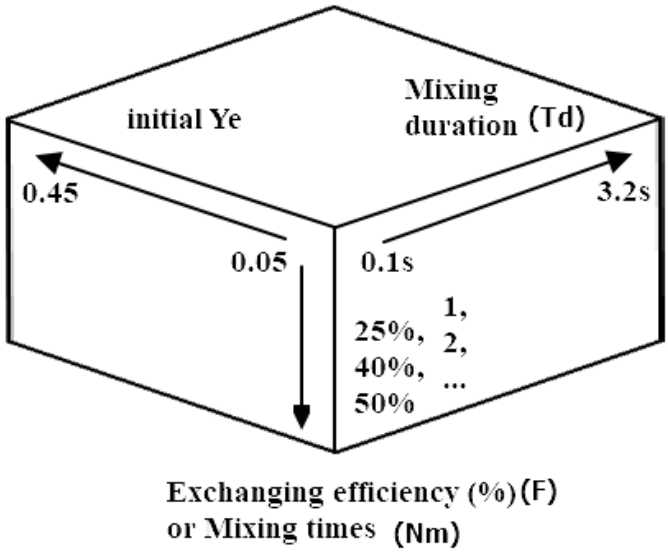

Figure 2.1: 3D array of parameter configuration
A cube-like 3D array, at "initial Ye" it have ten available initial combinations, at "mixing duration T_d" it have five possible duration, and "exchanging efficiency F_m, if we fix N_m (or mixing times N_m, if we fix F_m)", have three available (or more) chooses, so in this cube like 3D array will have more than hundred available data for our investigation.

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2.2 Program implementation

The implementation of our toy model require to extend the original nucleosynthesis simulation code. In original code used in [Giuliani et al., 2020]. We expand the code from evolving one fluid at a time to evolving two different fluids in one simulating run, not simultaneously but sequentially :

1. Firstly, we start evolving first fluid.
2. When mixing happened (mixing's time reached), the first fluid's evolving will be paused and its results such as 1.pausing-time 2.temperature 3.density 4.abundance, will be recorded into an outer-layer array.
3. And then begin second fluid evolving.
4. When mixing time reached again, the second fluid's evolving paused and be recorded as well.
5. Then next both fluids' abundance will be extracted to proceed exchanging.
6. As the exchange complete, both results abundance will replace the records in the array.
7. And the next stage (return to 1)will use these mixed abundances to repeat the same method to evolving. (Figure 2.2)

In a most situation, we usually cannot distinguish the nucleosynthesis yield of different fluid events in the multiple fluids combine system. So, in our final abundance distribution, we take an averaged abundance value for two fluids, no matter what case it is.

For other hydrodynamical expansion history of the two fluids other than Y_e, we take an analytically formulated representative one from [Wu et al., 2019], which has an initial density $\rho \simeq 1.03 \times 10^8$ (g cm^{-3}) and an expansion timescale of $\simeq 10$ ms.

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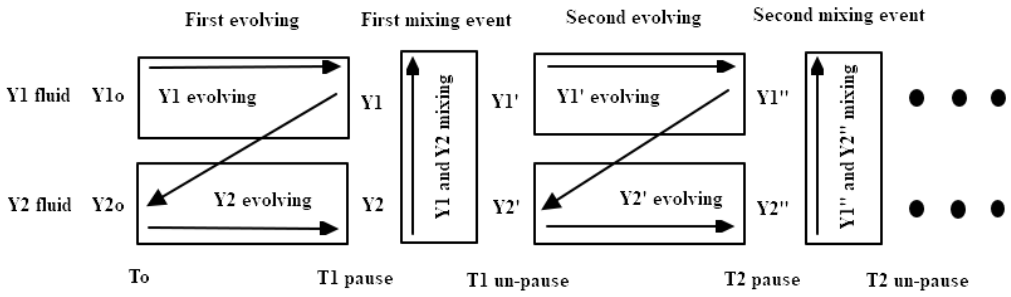

Figure 2.2: Program operating procedure
This figure show how our model processed simulation, both fluids evolve from starting point T_0 'til pause time $T1$, after exchanging at $T1$ they restart evolving to next pause time $T2$.

We start our calculations at an initial temperature of 8 GK and assume the initial abundances given by the nuclear statistical equilibrium condition [Cowan et al., 2021, Wu et al., 2019]. The corresponding entropy S varies between 10.93([k_b]) and 4.21([k_b]) for our chosen Y_e values.

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Chapter 3

Result Analysis and Discussion

The goal of the present work is to study the simulation result from the previous preparation, to clarify the mixing effect from altered nucleosynthesis path in exchanged fluids. In this chapter, we expect to see the different mixing effect that under the different mixing conditions compare to the case without mixing. These mixing cases are differ by non-identical initial Y_e composition, multiple mixing duration T_d, exchanging efficiency F_m, f_m and mixing times N_m. We will discuss two examples in the following sections, (1) two fluids exchange completely, to produce the "complete mixing". (2) partially exchange for both fluids, "incomplete mixing".

3.1 Evolving single fluid without mixing

Before we begin our discussion about mixing examples, here we make a additional discuss about the case without mixing. Every single fluid with different initial Y_e has a different neutron fraction Y_N, where $Y_N \equiv n_n/n_b$, and n_n (n_b) is the neutron (baryon) number density, resulting from different r-process duration, e.g. the lower initial Y_e the longer r-process lifetime. The lower initial Y_e means higher Y_N, which has a larger volume of neutron for r-process nucleosynthesis, lead to the longer r-process than the higher initial Y_e one(Table.3.1). As a result, it can synthesize toward heavier nuclei and has a larger abundance $Y(A)$ on large nucleon numbers

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A(Fig.3.1).

For a two-fluid system without mixing, its overall yields are simply the direct average of any of these two curves. In Fig. 3.2, we show the evolution of the neutron-to-seed ratio $R_{n/s}$ for these cases. It clearly illustrates that for a fluid with a lower Y_e, its r-process duration last longer. Defining the r-process duration as the time it takes for $R_{n/s}$ drops to 1, we show in Table 3.1 the r-process end times for different initial Y_e.

Table 3.1: r-process terminate time with different initial Y_e

Different initial Y_e have different r-process lifetimes. In our particular trajectory [Wu et al., 2019], the lifetime of the r-process has this relation table, and end time roughly has an exponential decrease corresponds with Y_e.

Initial Y_e	0.05	0.1	0.15	0.175	0.25	0.3	0.35	0.4	0.45
r-process end time (s)	1.110	0.709	0.456	0.377	0.139	0.082	0.036	0.011	0.002

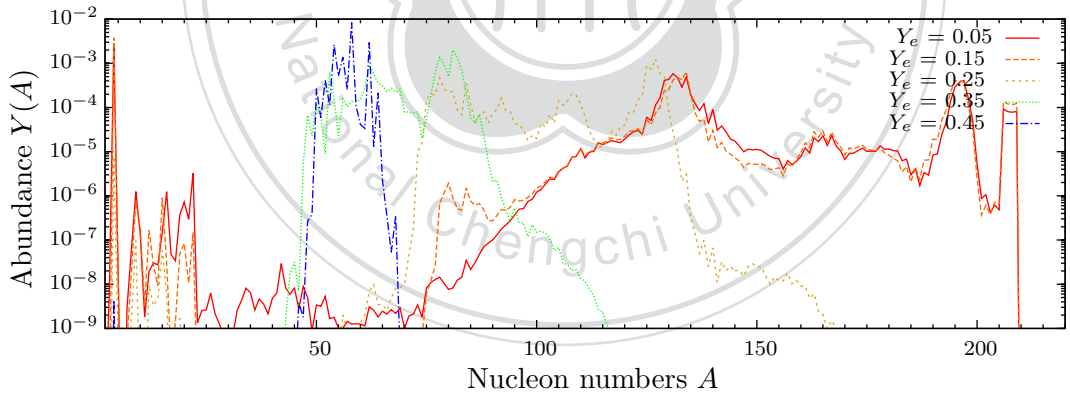

Figure 3.1: Final abundance distribution $Y(A)$ for single-fluid cases with different initial Y_e.

3.2 Complete mixing for two fluids system

We define the complete mixing as mix 100 percent($F_m = 100\%$) in one duration, or mix 50 percent for each fluid in one duration. Here we choose two initial com-

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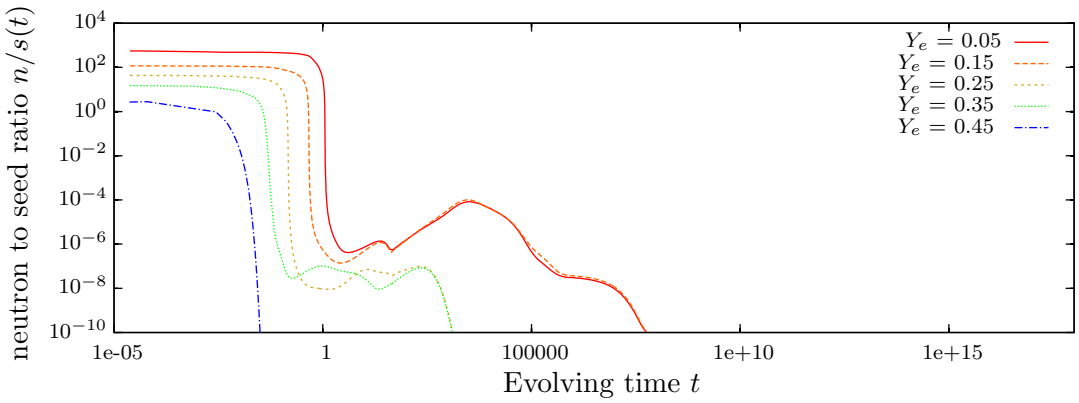

Figure 3.2: Evolution of the neutron-to-seed ratio $R_{n/s}$ for cases with different initial Y_e.

binations of Y_e 0.15+0.35 and 0.25+0.35 under 3 different duration (1)0.32s (2)1.0s (3)1.7s, then compare them with the case without mixing as our first discuss example.(Fig 3.3)

From Fig 3.3, the figure displays the "mixing effect" does appear at the final abundance distribution and corresponds with T_d and initial Y_e. From the left chart, T_d=0.32s(dark-magenta line), the one that is lower than 1.0s(purple line) and 1.7s(violet line), its final abundance is more distribute over high nucleon numbers A. It produces more heavy elements compared to the one without mixing(red line). As for the other lines from both the left and right charts, it does not show much difference from the case without mixing.

The reason behind this effect is that these fluids have different r-process lifetimes as we discussed in the previous section(table 3.1), which means these fluids do not end their r-process at the same time, causing a time gap between two fluids' r-process.

If the mixing happens at one fluid(we call it first fluid in the following sections) during its r-process, but the other fluid(we call it second fluid in the following sections) has finished its r-process, the first fluid will provide additional free neutron(Fig 3.4), to bring the second fluid back to further neutron capture. The second fluid will be able to continue nucleosynthesis and proceed to heavier nuclei, making the final

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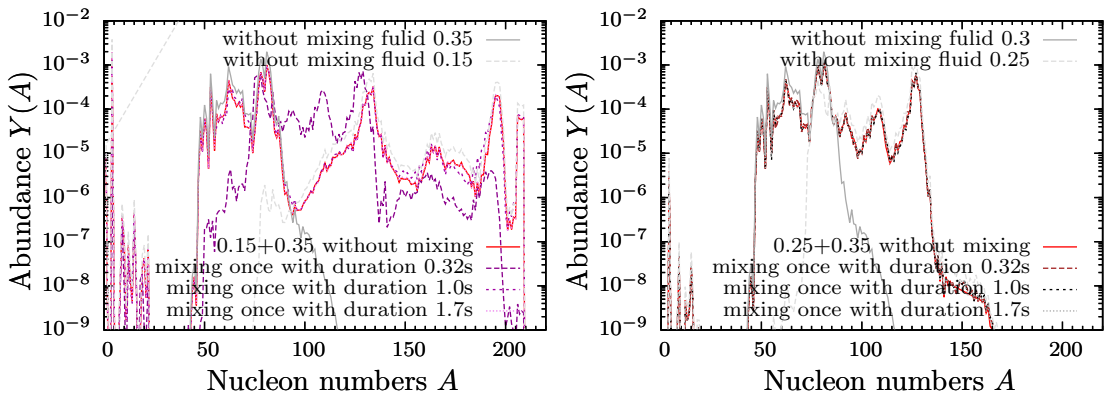

Figure 3.3: Other two combinations of complete mixing.
The left plot has three mixing scales in one, 0.32s(dark-magenta) have major boosting cause it within r-process, 1.0s(purple) have minor influence cause near r-process end, and 1.7s(violet) have no mixing effect cause r-process terminate. For right plot is pretty simple, all of them fall out r-process, so all three duration didn't affect abundance distribution.

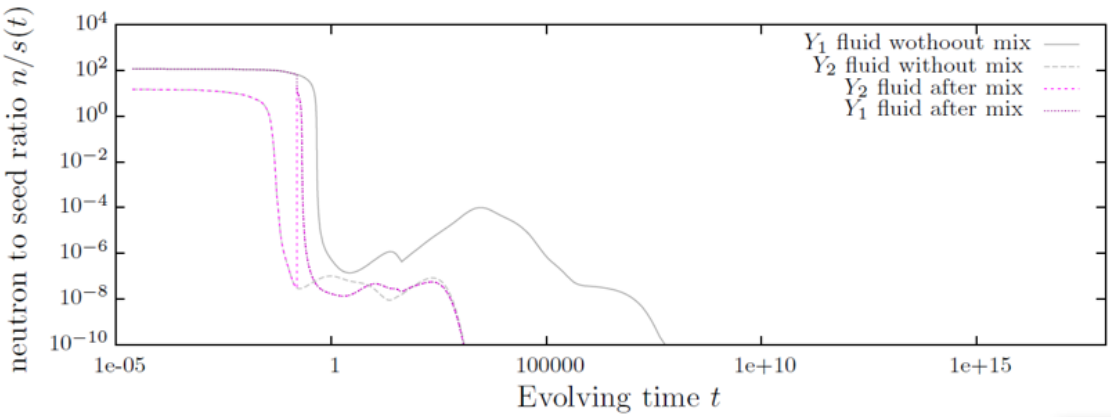

Figure 3.4: neutron-to-seed ratio v.s. evolving time.
This figure is base on fig 3.3's condition, 0.15+0.35 mix with $T_d = 0.32$. The purple dash line is initial $Y_e = 0.35$'s fluid after mixing, and the purple solid line is initial $Y_e = 0.15$'s fluid after mixing.

abundance distribution shift toward larger nucleon numbers A. We call this mixing effect "boosting", as it boosts fluids to synthesize heavier elements. But if mixing happens at both fluids are out of their r-process duration, due to their remaining neutrons are not enough to bring r-process's neutron capture back, the mixing does not have a significant effect on r-process synthesis. As the result, the mixed final

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abundance distribution is identical with the case without mixing.

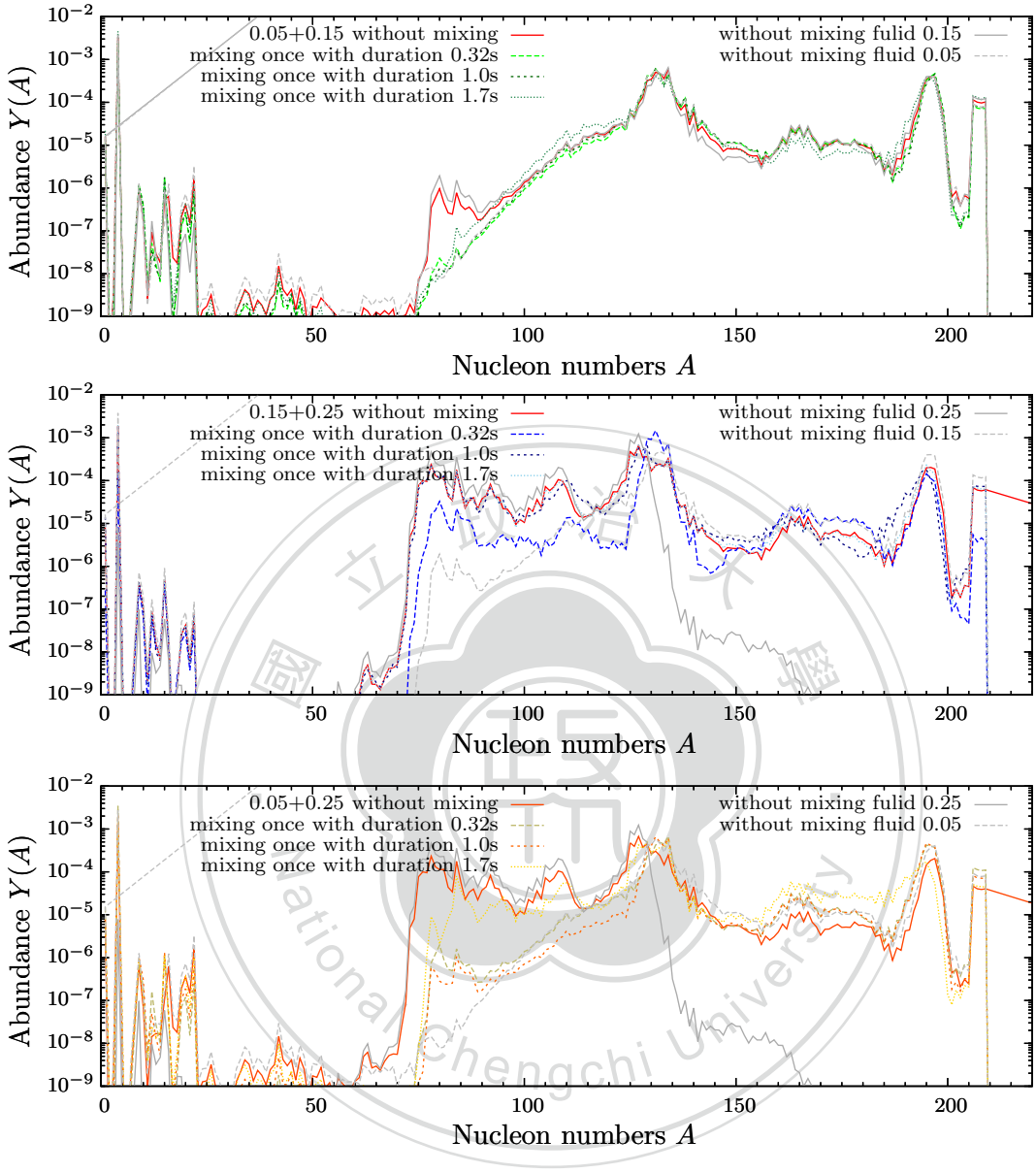

Figure 3.5: Three different combinations of complete mixing.
The upper plots show the final abundance distribution of three different combination cases, as (upper) 0.05+0.15, (center) 0.15+0.25 and (lower) 0.05+0.25, and with three possible duration $T_d(s)$, (green, blue, dark-khaki) 0.32s, (forest-green, navy, orange) 1.0s and (sea-green, sky-blue, gold) 1.7s.

Such effect also can be seen in figure 3.5, here we set (1.upper)0.05+0.15 (2.middle)0.15+0.25 (3.bottom)0.05+0.25 with 3 different T_d, to present another complete mixing example.

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In the middle part, the effect of boosting does appear in the 0.32s(blue) one and 1.0s(navy) one as compare to the case without mixing(red), both of their abundance distributions are shifting toward higher nucleon numbers. That means this effect is a standard result as a mixing happens at partly r-process still on. As for the 1.7s one (sky-blue), the line of final abundance distribution is nearly identical to the case without mixing, which means in this case mixing does not drastically affect the system's outcome because both fluids' r-process already ended. The 1.0s one's line is almost identical to the case without mixing and 1.7s one, but it still slightly effect by boosting than 1.7s one. Because as we proceed to mix, the exchange is happening right after the first fluid has finished its r-process for a while, and the second fluid's r-process has just ended, so there still plenty free neutron from later fluid to boost the other one's neutron capture. As the result, the fluid can synthesize a bit heavier nuclei than 1.7s one.

The boosting effect makes abundance distribution shift toward higher nucleon numbers, and under different conditions will have a variance level of boosting effect. In the bottom part, as the first fluid is still within the r-process, the 0.32s(khaki) one is mixing right after the second fluid's r-process just end, the 1.0s(orange) one is mixing when the second fluid's r-process end for a while, and the 1.7s(gold) one is mixing at farther from the second fluid's r-process end. The variance between these lines mainly depends on different free neutron abundance that can supply neutron capture. Such as the 0.32s case versus the 1.7s case at $A \sim 210$. After mixing, the second fluid gets more free neutron to synthesize heavier nuclei, and the 1.7s one gets less neutron to produce heavy elements.

There is another mixing situation in the upper part of fig 3.5. For the T_d=1.7s(sea-green) case, the boosting effect makes its final abundance shift toward higher nucleon numbers compare to without mixing(red). But for 0.32s and 1.0s(green and forest-green) are shift a bit toward lighter nuclei than without mixing. That is because both fluids are still within their r-process, the mixing itself average their remaining

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free neutrons, and make their final abundance distribution closer toward each other compare with the direct average of without mixing. So, the result seems like "averaging" both fluids' initial Y_e, and this mixing effect is heavily depending on the initial Y_e combination. If both fluids have a higher initial Y_e, the "averaging" effect will more likely to synthesize heavier nuclei.

To be noticed, as for 100% mixing total in the system(50% each fluid), mixing 1-time is all that matters, more mixing times just do not affect final abundance distribution, because after both fluids are equal, more mixing times just didn't change fluid's composition.

3.3 Incomplete mixing for two fluids system

Relative to complete mixing, we set those F_m are not 100%, both fluids do not have a complete exchange as the incomplete mixing. In the previous complete example, whole fluids do exchange completely in 1st mix, making any further exchange such as 2nd or 3rd mix would not affect the final outcome. In fact, in that situation the mixing times N_m become degenerate parameters, and lead to $F_m = f_m$.

But in this section, due to $F_m \neq$100%, the f_m that depends on mixing times N_m became non-constant, which means f_m will change if N_m also changes(Table2.1). Further more, the separation of duration making each mixing time with f_m land on different reaction regions, causing some mixture outcome or even balance out the final distribution. For example, in some of the multiple mixing, first mixing locates at "averaging" region, but the rest locate at other regions, it may overlap with the later reaction's result, and then we could see some mixture result in this kind of situations. In this section, we design two sets of F_m - 80% and 50% under multiple N_m such as mixing 2-times and 3-times, to get further discussion about how mixing affects the nucleosynthesis outcome with multiple mixing times.

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3.3.1 Mixing with F_m = 50% - halved mixing

We begin our example with F_m=50%, and use the similar configuration from the complete mixing case, with Y_e combination (1,upper)0.05+0.15, (2,middle)0.15+0.25, (3,bottom)0.15+0.35, and with duration T_d as 0.32s, 1.0s, 1.7s. In this section, the figures we display are discussed one T_d at a time, different lines in each parts are presenting different mixing times N_m.

Similar to the right part of fig 3.3, fig 3.6's abundance distribution is nearly identical with the case without mixing, especially the middle and bottom parts. The cases in middle and bottom part's mixing are mostly happening at both fluids have finished their r-process, so the mixing effect does not affect final abundance distribution. Except for the bottom's mix 3-times, when the first mix happens, its first fluid still gets enough remaining free neutron to boost the second fluid's ended r-process, and allow it to produce heavier elements. But as the only first mix can affect fluids' r-process outcome, the total exchange percentage will be 20.64% leaser than the F_m = 50% we design in this section.

As for fig 3.6's upper part, the mixing 1-time is a regular boosting case with F_m, and the mixing 2-times is another case that only the first boosting mix will affect the final outcome, the second mix just falls out both fluids' r-process, let boosting less effective than 1-time case. The mixing 3-times is a bit complicated, the first mix just land on the averaging region right before the r-process end, and make the majority effect on final abundance, the second mix is happening at the later boosting region, and the third mixing happens even later that might fall out both fluids' r-process. Such conditions could lead to both mixing effects overlap each other, and potentially alter the r-process outcome. As multiple mixing effects appear in single T_d duration, the first mix will have a larger influence on the final outcome than the second mix, making the first mix in the multiple mixing case has the dominant rule in the whole T_d duration of synthesis. But since current initial Y_e combination has a large number of free neutrons, that mixing effects hardly appear

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in the final outcome, so mostly the cases except mix 1-time are nearly identical with the case without mixing.

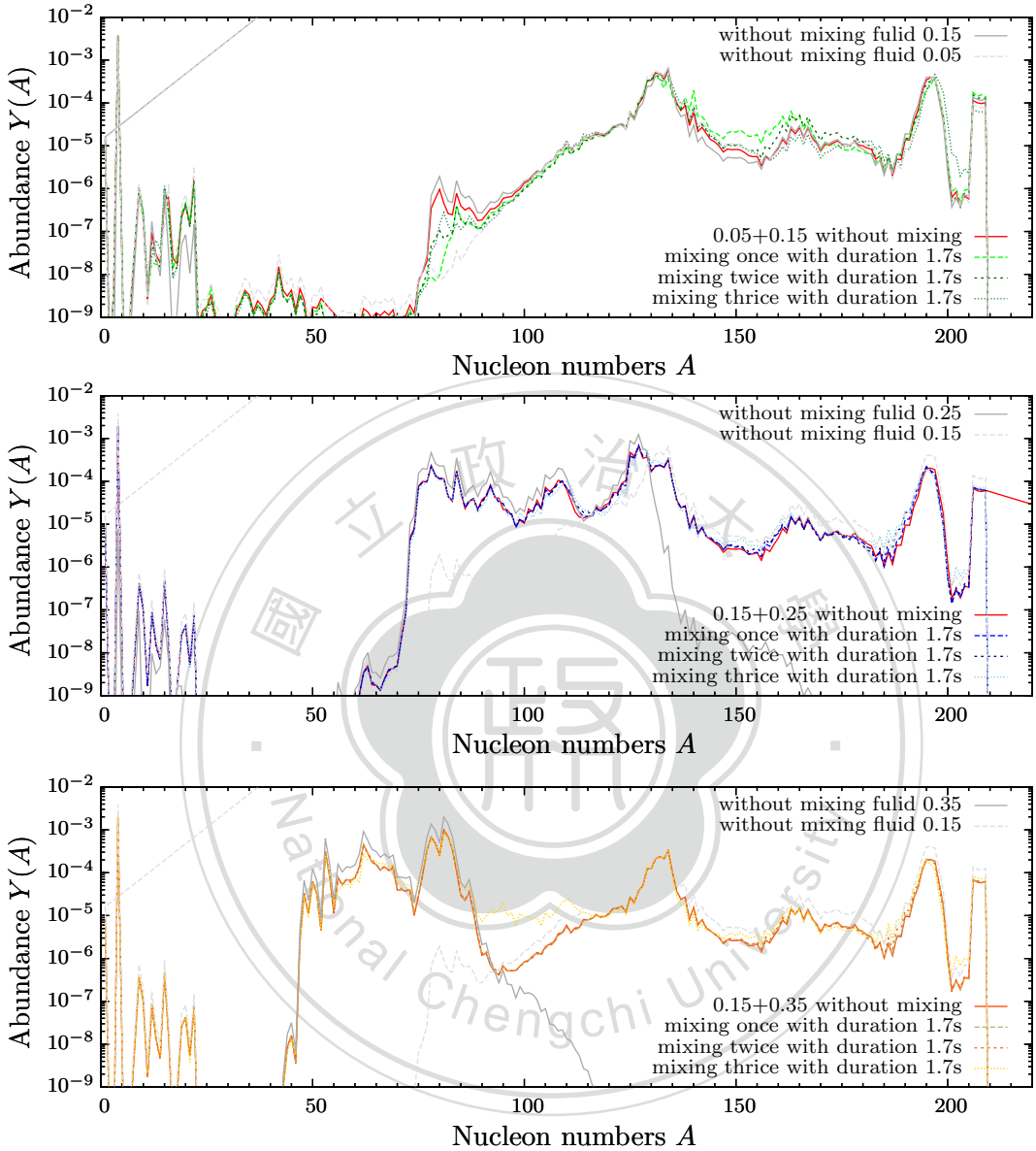

Figure 3.6: Three different combinations of incomplete mixing with T_d=1.7s. The final abundance distribution of three different initial Y_e and different N_m, with same T_d=1.7s, as (upper) 0.05+0.15, (center) 0.15+0.25 and (lower) 0.15+0.35.

We proceed to another $F_m = 50\%$ example as $T_d = 1.0s$ cases. On the upper part of Fig 3.7, due to both fluids' initial Y_e, the mixing effects are hardly affecting the curvature of abundance distribution, but there is still a minor displacement between these lines. The mixing 2-times' has a bit heavier nuclei than mixing 3-times',

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the mixing 2-times' get a larger boosting effect than an averaging effect that can synthesize toward higher nucleon number. Although under such initial condition, the averaging still play the major role within mixing 3-times', the later boosting with f_m is less significant on the final outcome.

The middle part of fig 3.7 has a similar feather as fig 3.6's bottom part, the second mixing of mixing 2-times has already dropped out r-process duration, only the first mixing can affect the r-process's nucleosynthesis. So there is only 29.28% fluid exchanged during this duration, lesser than F_m we design earlier, make the boosting effect not effective than mix with $F_m = 50\%$. Mixing 3-times has a similar situation, only the first mix with 20.64% can affect the final outcome, so the boosting effect becomes even lower than mixing 2-times.

The result at the bottom part is quite straightforward. Similar to the middle part, there is only the first mixing which has boosting effect that can affect the r-process outcome of the mixing 2-times and the 3-times case, the rest of mixing just has a limit effect on the final abundance. Moreover, because of lower f_m, the mixing 2-times' boosting effect is slightly higher than 3-times'.

The next case will be T_d=0.32s. As fig 3.8 displays each lines with different N_m are close together when under the same initial condition. Especially in the upper part, their mixing mostly happens at averaging region and mix with short T_d, causing no boosting effect and only have the minor shift from without mixing. Pretty similar to complete mixing 0.05+0.15 case at T_d=0.32s or T_d=1.0s(Fig.3.3), except higher F_m that make mixing has a larger effect than current example.

For the middle part, the first mixing happens at an averaging region like the mixing 2-times and mixing 3-times cases, while the rest mixings locate at the later boosting region. Although this final abundance outcome has the overlapped effect of averaging and boosting, the final distribution is still quite closing to each other due to short evolving time, which reduces the effectiveness of both mixings.

At the bottom part of the figure, these lines are very close to each other. With

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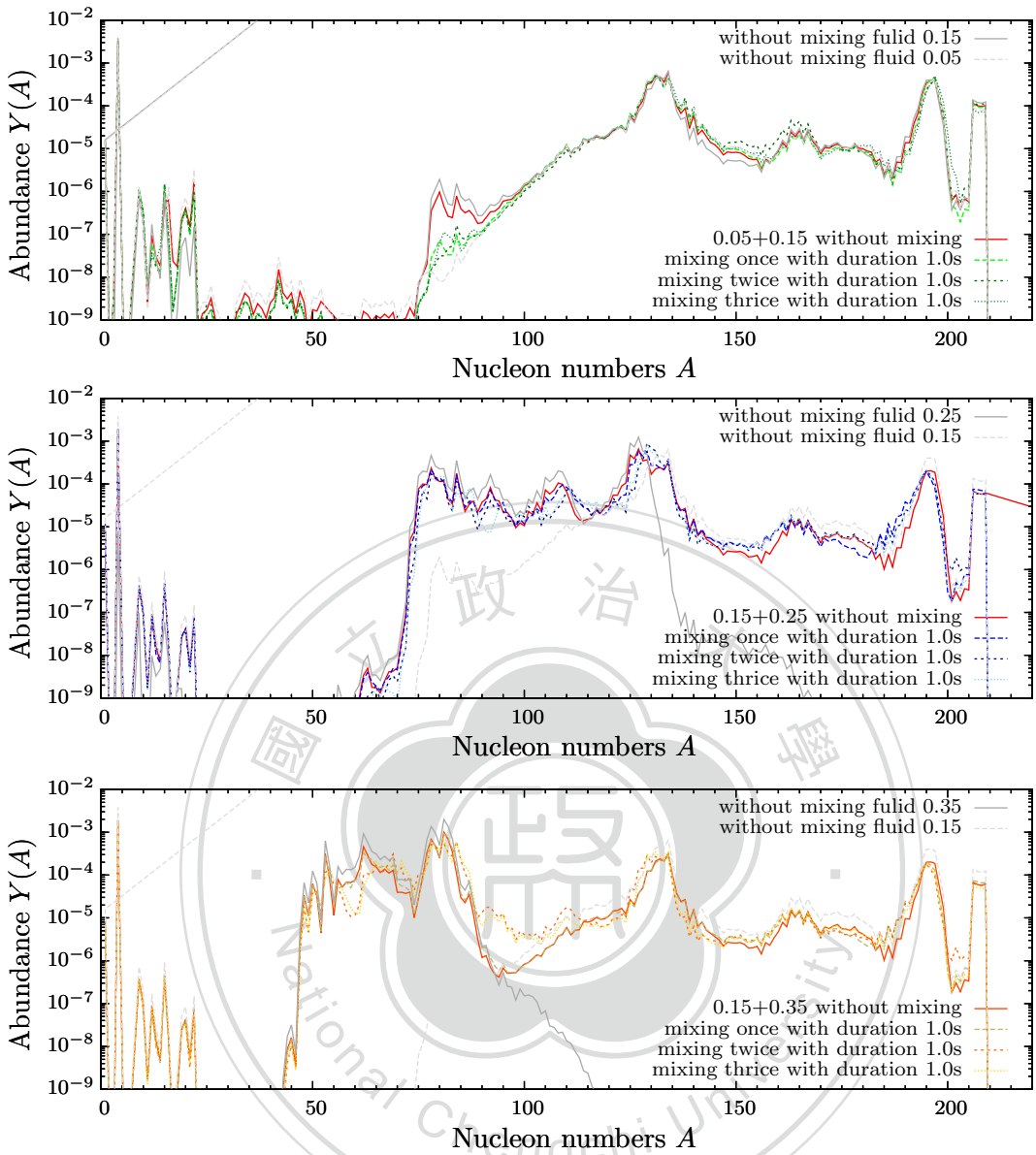

Figure 3.7: Three different combinations of incomplete mixing with T_d=1.0s. The final abundance distribution of three different initial Y_e and different N_m, with same T_d=1.0s, as (upper) 0.05+0.15, (center) 0.15+0.25 and (lower) 0.15+0.35.

the previous discussion, the mixings of these different N_m lines are all locate at boosting region, so their final outcomes are almost the same, except for the minor displacement between them which cause by the different happening times of mixing and different effect scale with f_m.

The discussion we have in this section by far, is the mixing effects are pretty similar with complete mixing, but with mixing times N_m involve. As N_m is corre-

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sponding with f_m, the more N_m is the earlier the first mix will be, and the more N_m likely to locate at different mixing region that will lead to overlap result. Each mixing time's percentage f_m will also drop, making the first mix has the majority effect potentially. But if in lower Y_e's initial condition and shorter T_d duration, the mixing effect will become lesser in final abundance distribution.

3.3.2 Mixing with $F_m = 80\%$

As we analyzed complete mixing($F_m = 100\%$) and half mixing($F_m = 50\%$) cases, we increase F_m to 80% to be another incomplete example.

The figures in this section(fig 3.9, fig 3.10, fig 3.11) are well related to F_m=50% cases(fig 3.6, fig 3.7, fig 3.8), only with a higher exchanging percentage that makes mixing effects from F_m=50% are more significant on final abundance.

For example, in fig 3.9 the middle and the bottom parts are nearly identical with the case without mixing, and their mixing 3-times' have a minor boosting to produce heavier elements. As the upper part, the distributions are still pretty much the same, but for mixing 1-time' the larger boosting effect make it can proceed to even heavier nuclei like from lanthanide peak to near the third peek.

As the T_d=1.0s cases in fig 3.10, these final distribution lines are very similar with fig 3.7's $F_m = 50\%$ cases, only with the higher F_m and f_m that can visibly both increase mixing effects on the final abundance distribution.

Similar to previous cases, the cases of 0.32s in fig 3.11 have the same feature as fig 3.8. The boosting effect is more effective at the bottom part, causing fluids can synthesize heavier elements. As for the middle part, the increased F_m let the displacement more obviously even the mixture of two mixing effects. Compare to fig 3.8, the upper part does have many differences as current initial condition and T_d duration, but there is still a tiny change at the first peak, it becomes lower than fig 3.8.

In the end, in the two-fluid multiple mixing situations, the first mixing will let

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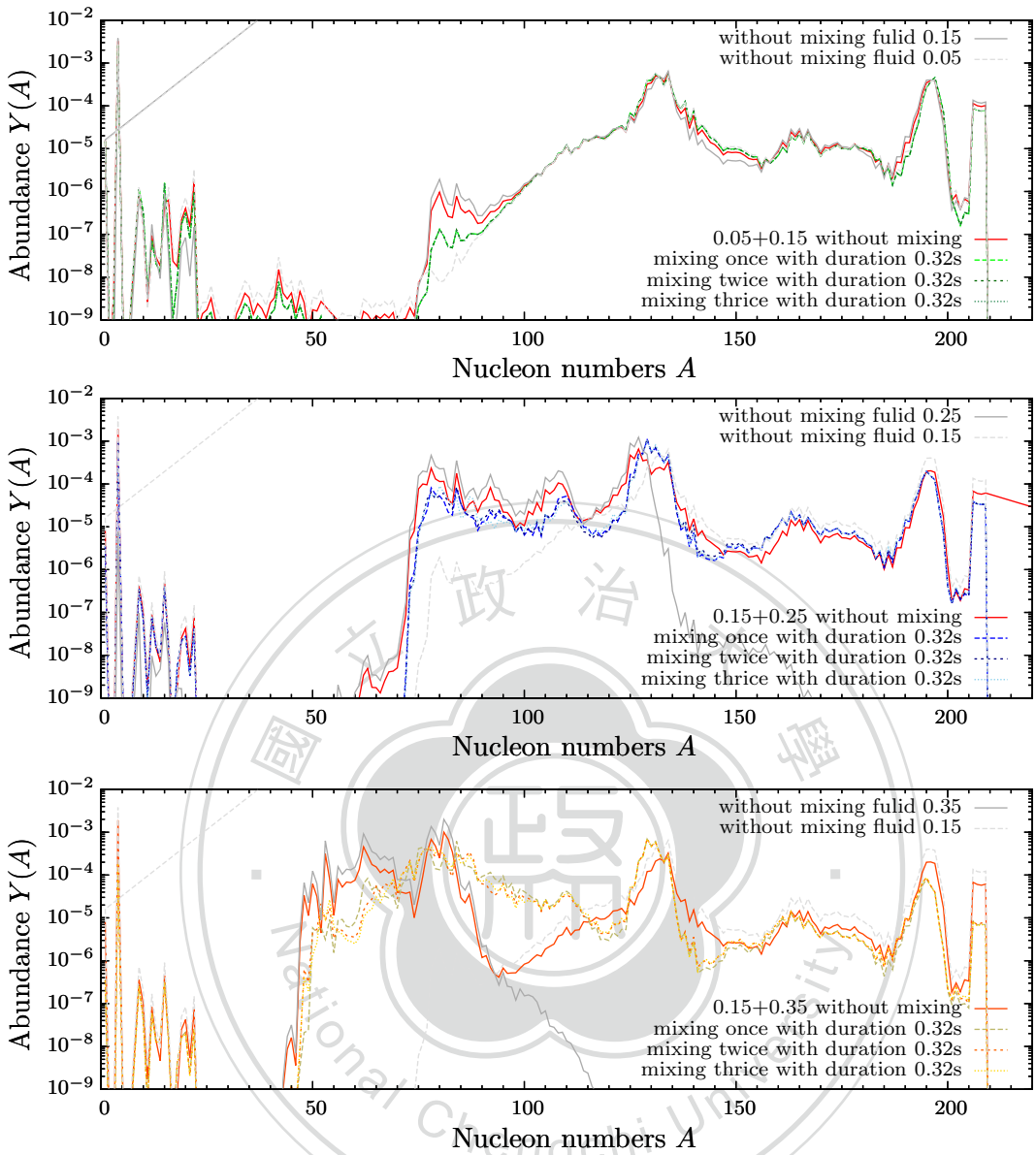

Figure 3.8: Three different combinations of incomplete mixing with T_d=0.32. This figure shows the final abundance distribution of three different initial Y_e with the same T_d, as (upper) 0.05+0.15, (center) 0.15+0.25 and (lower) 0.15+0.35. There were three examples of mixing times N_m, (green, blue, dark-khaki) mixing once, (forest-green, navy, orange) mixing 2-times, and (sea-green, sky-blue, gold) mixing 3-times.

the longer(shorter) r-process fluid's r-process lifetime become a bit shorter(longer), due to exchanging composition with a decrease(increase) its remaining free neutron. So in this chapter's cases, the fluid's r-process lifetime might be even shorter than the single fluid's r-process in sec.3.1 after mixing, causing the rest of mixing could

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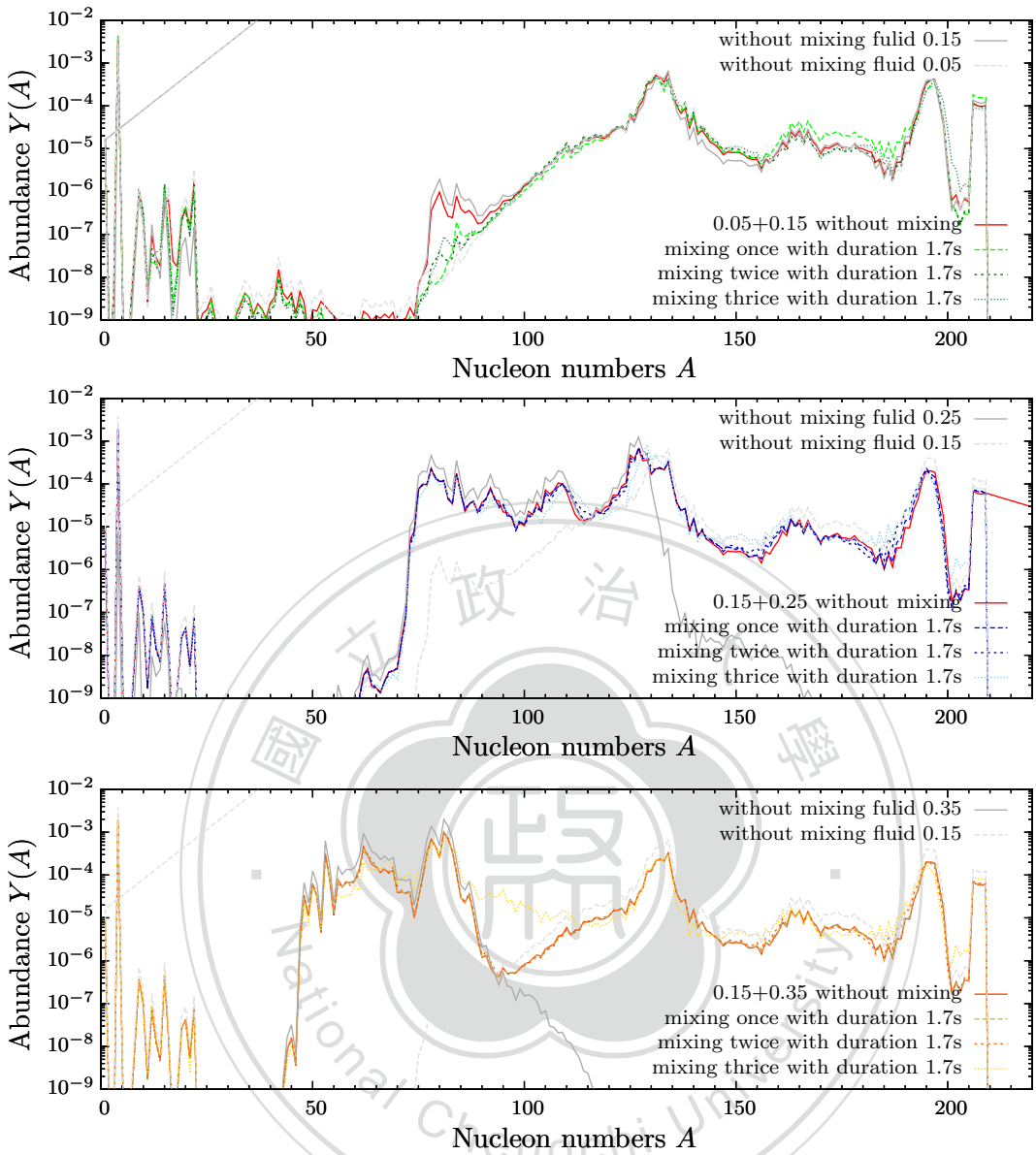

Figure 3.9: Three different combinations of incomplete mixing with T_d=1.7s. The final abundance distribution of three different initial Y_e and different N_m, with same T_d=1.7s, as (upper) 0.05+0.15, (center) 0.15+0.25 and (lower) 0.15+0.35.

even locate at a later mixing effect region.

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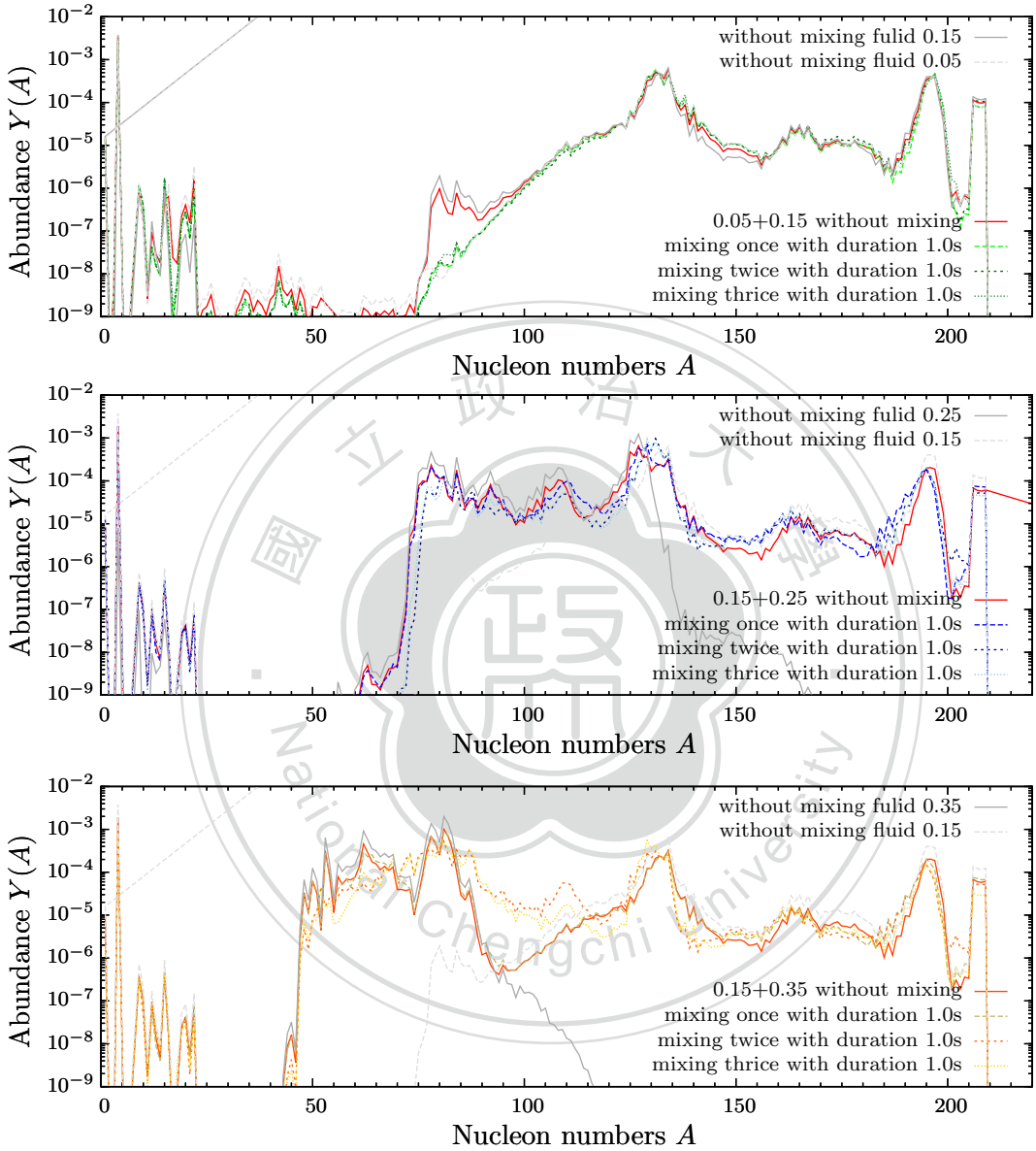

Figure 3.10: Three different combinations of incomplete mixing with T_d=1.0s. The final abundance distribution of three different initial Y_e and different N_m, with same T_d=1.0s, as (upper) 0.05+0.15, (center) 0.15+0.25 and (bottom) 0.15+0.35.

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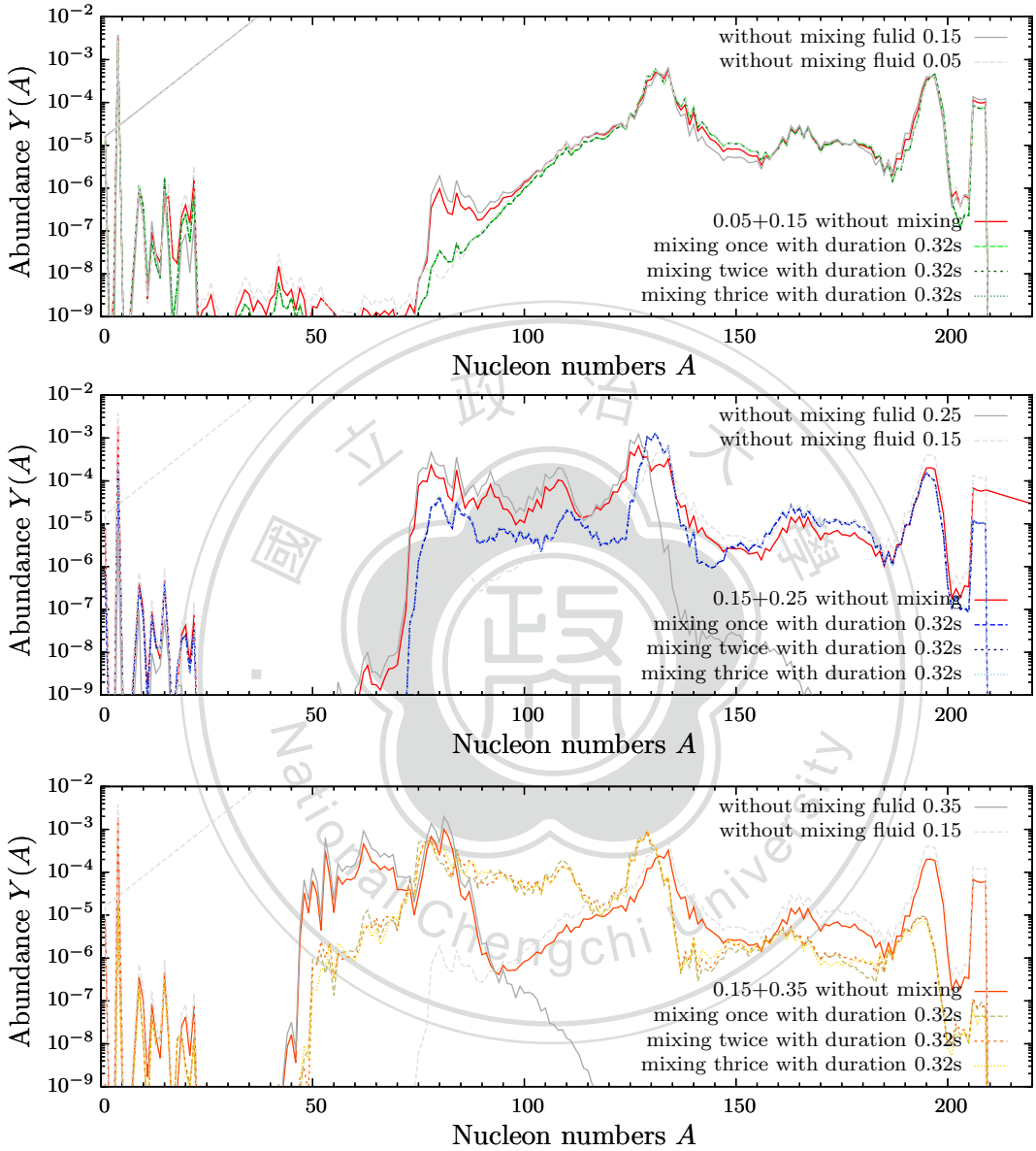

Figure 3.11: Three different combinations of incomplete mixing with T_d=0.32. The final abundance distribution of three different initial Y_e and different N_m, with same T_d=0.32s, as (upper) 0.05+0.15, (center) 0.15+0.25 and (lower) 0.15+0.35.

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Chapter 4

Conclusion and Outlook

4.1 Conclusion

In this thesis work, we have studied the potential effect of composition mixing on the r-process nucleosynthesis outcome with a simply two-fluid toy model. We found that depending on the chosen Y_e values of the two fluids, mixings in systems that have different mixing parameters can lead to different impact on the r-process outcome. For systems that undergo a complete mixing, if mixing happen when one fluid is still in r-process while the other one has finished its r-process, the mixing will brings free neutrons from the fluid that is still within the r-process (initially lower Y_e) to the other fluid that has used out its initial neutrons (initially higher Y_e). Thus, this allows to re-start the r-process in the fluid that has higher Y_e initially and thus "boost" its production of heavy nuclei. This can largely influence the system's final abundance distribution if the initial Ye of the two fluids are rather different. The exact degree of the boosting effect can depend on the relative initial Y_e of the fluids as well as the exact time when the mixing happens. If exchanging happen when both fluids are still within r-process, the impact of the mixing is subdominant and the results are generally similar to cases without mixing.

If mixing happens outside both fluid's r-process, there is no significant chance of

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r-process reaction after two fluids exchange, and the final abundance distributions are only slightly affected by the mixing process.

For the cases with incomplete mixing where $F_m < 100\%$, a total mixed percentage of F_m can be divided into several mixing episodes, each of which mixes a smaller fraction of the fluids f_m. Thus, we also explored how this can affect the our results. We found that in general our results do not sensitively depend on the number of sub-mixings N_m and the main features are broadly similar to the cases with complete mixing.

Another effect of mixing is that it obviously makes the two fluids r-process conditions to become more similar. Thus, overall it will shorten the r-process duration of the entire system.

4.2 Outlook

Although we have shown that composition mixings can potentially affect the r-process outcome within our simple two-fluid system, several aspects remain to be further studied in order to understand how a potential mixing in a realistic BNSM system can leave impact on its r-process outcome. Here we list a few potential directions that can be further investigated beyond the scope of this thesis work. First, a straightforward extension is to enlarge our toy-model system and include more fluids within a smooth Y_e distribution. Although we expect that main conclusion that the mixing can potentially boost the production of heavy nuclei will remain, this needs further confirmation.

Second, we may try to link our toy model parameters to the physical parameters of the system such as the jet energy, jet opening angles, amount of ejecta, etc., by trying to discuss with experts who conduct numerical simulation of jet penetrating the ejecta. This may allow us to further potential link the nucleosynthesis results to the physical properties of the system.

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Last but not the least, the ultimate goal will be to couple the r-process nucleosynthesis reaction network with hydrodynmical simulations including the interaction of jets and ejecta, to see whether the nuclear energy released during the r-process may affect the mixing caused by jet penetration.

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