Gamma-Ray Diagnostics of r-process Nucleosynthesis in the Remnants of Galactic Binary Neutron-star Mergers

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Received 2022 March 3; revised 2022 April 26; accepted 2022 May 10; published 2022 July 7

Abstract

We perform a full nuclear-network numerical calculation of the r-process nuclei in binary neutron-star mergers (NSMs), with the aim of estimating gamma-ray emissions from the remnants of Galactic NSMs up to $10^6$ yr old. The nucleosynthesis calculation of 4070 nuclei is adopted to provide the elemental composition ratios of nuclei with an electron fraction $Y_e$ between 0.10 and 0.45. The decay processes of 3237 unstable nuclei are simulated to extract the gamma-ray spectra. As a result, the NSMs have different spectral colors in the gamma-ray band from various other astronomical objects at less than $10^5$ yr old. In addition, we propose a new line diagnostic method for $Y_e$ that uses the line ratios of either $^{137m}$Ba/$^{85}$K or $^{243}$Am/$^{50}$mCo, which become larger than unity for young and old r-process sites, respectively, with a low-$Y_e$ environment. From an estimation of the distance limit for gamma-ray observations as a function of age, the high sensitivity in the sub-megaelectronvolt band, at approximately $10^{-9}$ photons s$^{-1}$ cm$^{-2}$ or $10^{-15}$ erg s$^{-1}$ cm$^{-2}$, is required to cover all the NSM remnants in our Galaxy, if we assume that the population of NSMs by Wu et al. A gamma-ray survey with sensitivities of $10^{-8}$–$10^{-7}$ photons s$^{-1}$ cm$^{-2}$ or $10^{-14}$–$10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the 70–4000 keV band is expected to find emissions from at least one NSM remnant under the assumption of an NSM rate of 30 Myr$^{-1}$. The feasibility of gamma-ray missions observing Galactic NSMs is also studied.

Unified Astronomy Thesaurus concepts: R-process (1324); Gravitational wave sources (677); Neutron stars (1108); Nuclear astrophysics (1129); Nucleosynthesis (1131)

Supporting material: data behind figure

1. Introduction

Elements heavier than Bi exist in our universe, but their origin remains a mystery. Most cosmic isotopes heavier than the iron group are expected to be created by the rapid-neutron capture process, also known as the r-process. The iron group is expected to be created by the rapid-neutron capture process in the universe. From an estimation of the distance limit for gamma-ray observations as a function of age, the high sensitivity in the sub-megaelectronvolt band, at approximately $10^{-9}$ photons s$^{-1}$ cm$^{-2}$ or $10^{-15}$ erg s$^{-1}$ cm$^{-2}$, is required to cover all the NSM remnants in our Galaxy, if we assume that the population of NSMs by Wu et al. A gamma-ray survey with sensitivities of $10^{-8}$–$10^{-7}$ photons s$^{-1}$ cm$^{-2}$ or $10^{-14}$–$10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the 70–4000 keV band is expected to find emissions from at least one NSM remnant under the assumption of an NSM rate of 30 Myr$^{-1}$. The feasibility of gamma-ray missions observing Galactic NSMs is also studied.

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1. Introduction

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According to theoretical estimates of the gamma-ray flux from binary NSMs (Hotokezaka et al. 2016), the gamma-ray radiation immediately following a merging event is very dim at about $10^{-8}$–$10^{-7}$ photons s$^{-1}$ cm$^{-2}$ keV$^{-1}$, even at an extremely close distance $d$ of 3 Mpc. This flux is comparable to or below what the sensitivities of current and near-future megaelectronvolt missions can detect. The precise measurements of photon energies are, in principle, rather difficult in the megaelectronvolt band, where Compton scattering dominates over the photon-absorption process. Therefore, the ability to detect gamma-rays from NSMs by an immediate follow-up observation (a Target-of-opportunity observation; ToO) would be limited by the sensitivity of the gamma-ray instruments. Instead, a non-ToO observation of gamma-rays from long-lived nuclei in NSMs would be an alternative way to survey
r-process sites, and this has been proposed by Wu et al. (2019) and Wang et al. (2020). The gamma-ray luminosity from nuclei with long lifetimes, on the order of $10^{7} - 10^{8}$ yr, becomes much lower than that from short-lived nuclei, but if we limit the survey area within our Galaxy ($d \lesssim 10$ kpc), then the gamma-ray flux in non-ToO observations is expected to become comparable to that required for ToO observations. Therefore, non-ToO observations should provide more sensitive gamma-ray surveys of NSMs because the exposure time (the accumulation time of signals) is not limited as it is in ToO observations. Another benefit of performing a non-ToO survey is the better identification of gamma-ray lines; we expect the effect of Doppler broadening to be smaller for older NSM remnants than for very young NSMs.

Here, we focus on the non-ToO survey of gamma-rays from r-process nuclei in a possible Galactic NSM remnant. In this paper, we estimate gamma-ray emissions from Galactic NSM remnants in an older age range than in previous work (Hotokezaka et al. 2016; Wang et al. 2020) by using nuclear-network numerical calculations with a complete nuclear database. This paper also aims to provide gamma-ray diagnostic methods for NSMs, showing the required sensitivities for future gamma-ray observatories. In our study, we assume that gamma-ray instruments have a wider field-of-view (FOV) than the object size of the NSM remnants, which are larger than early NSMs in a ToO observation. We also assume that the instruments accumulate all of the gamma-ray emissions from the NSM remnants, even though the nuclei may mix with the circumstellar medium (CSM) during the evolution of the remnants.

The rest of this paper is organized as follows. In Section 2, we summarize our environments and procedures for the nuclear-network numerical calculation and show the results for gamma-ray emissions from NSM remnants. In Section 3, we present the gamma-ray diagnostics, which utilize spectral color to identify NSM remnants and provide the line properties for estimating the age $t$ and $Y_{e}$. In Section 4, we discuss the survey distance and coverage in our Galaxy permitted by the instrument sensitivities, the corresponding limitation of the NSM rate in our Galaxy, and expectations for future missions.

### 2. Numerical Estimation of Gamma-Rays from NSM Remnants

#### 2.1. Overview of Numerical Calculation

To estimate the gamma-ray emissions from binary NSM remnants of various ages, we performed a numerical simulation comprising the following three steps: (1) calculation of the mass distribution of r-process nuclei for NSMs at $t = 1$ yr, (2) calculation of the decay processes of unstable nuclei emitting gamma-rays, and (3) a simple calculation of the radiation transfer of gamma-rays from NSMs.

For the first step, we adopted the nucleosynthesis calculation for around 4070 nuclei performed by Fujimoto et al. (2007), which was cooled using the adiabatic expansion modeled from Freiburghaus et al. (1999) to provide the elemental composition ratios of nuclei for $Y_{e} = 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40$, and 0.45. This estimation assumes that the initial environment has a temperature of $9 \times 10^{9}$ K, a radius of 100 km, entropy per baryon of 10 $k_{B}$, where $k_{B}$ is the Boltzmann constant, and a velocity of $2 \times 10^{9}$ cm s$^{-1}$, along with the initial abundances of the 4070 nuclei in nuclear statistical equilibrium. As a result, the calculation provides the mass fractions at $t = 1$ yr evaluated with the nuclear reaction network (network A in Fujimoto et al. 2007), by using $Y_{e} = 0.10 - 0.45$ in steps of 0.05. To set up the mass distribution of nuclei for the NSMs at $t = 1$ yr, we blended the nuclei with the mass fraction using the $Y_{e}$ provided in Wanajo et al. (2014). Specifically, the fractions are 4.54%, 4.85%, 14.6%, 29.7%, 10.3%, 25.1%, 10.5%, and 0.33% for $Y_{e} = 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40$, and 0.45, respectively.

Note that this $Y_{e}$-fraction model by Wanajo et al. (2014) describes a slightly less neutron-rich environment than those by the recent dynamical-ejecta models after the kilonova observations of the gravitational event GW170817, such as four models in Kullmann et al. (2022) under two kinds of equations of state, density dependent 2 (DD2; Hempel & Schaffner-Bielich 2010; Typel et al. 2010), and SFHo (Steiner et al. 2013). In this paper, we adopted the first one by Wanajo et al. (2014) as a pessimistic case for the r-process site, but changing the $Y_{e}$-fraction models does not change the conclusions from the gamma-ray spectra as tested in Section 3. Figure 1 shows the mass fraction of multiple nuclei at $t = 1$ yr generated in an NSM case, information that is given in the table of nuclides (neutron number $N$ versus atomic number $Z$). Using the same data set, Figure 2 summarizes the distribution of nuclei with mass number $A$ at $t = 1$ yr, showing the contributions of $Y_{e}$. This plot demonstrates that the environment with lower $Y_{e}$ contributes to the generation of heavier elements.

![Figure 1. The r-process nuclei in the NSM case at $t = 1.0$ yr](image1.png)

![Figure 2. Mass number distribution of the abundance for the NSM case at $t = 1.0$ yr, with $Y_{e}$ ∼ 0.1, 0.2, 0.3, and 0.4, shown in red, magenta, blue, and green, respectively.](image2.png)
For the second step, we simulated the decay processes of unstable nuclei, starting from the mass distribution at $t = 1$ yr calculated in the first step. We used the Decay Data File 2015 (DDF-2015; Katakura & Minato 2016) from the Japanese Evaluated Nuclear Data Library (Katakura 2012), which provides the decay profiles of 3237 nuclei up to $Z = 104$ (Rf). Here, we applied a correction to the gamma-ray information for 241Am; this error was reported in our study and was corrected in the next version of the database. The originality of this study lies in the comprehensiveness of nuclei treated in the calculation. In the nuclear-decay calculation, we adopted the $\alpha$ decay, $\beta^-$-decay, $\beta^+$-decay, electron capture, isomeric transition, and gamma-decay processes. In our calculation, the internal conversion process is ignored, which emits soft X-rays and makes a negligible contribution to the gamma-ray band. The neutron- and proton-emission processes are also ignored because they contribute to the very early phase, which is beyond the scope of this study. The spontaneous fission process may occur on $^{257}$Es, $^{258}$Cf, $^{254}$Cf, and $^{250}$Cm, but its contribution is negligible. Thus, this process is also excluded from our calculation. In addition, we do not calculate the gamma-ray emission from secondary electrons (electrons from $\beta$-decay, $\gamma$-rays, and so on) after the decay of unstable nuclei.

To verify the calculations in the second step, we refer to Figure 3, which represents the relative abundances of nuclei at $t = 10^3$, $10^6$, and $10^9$ yr, shown in green, blue, and thick black, respectively, compared with the semi-empirical abundance distribution of Beer et al. (1997).

Finally, the third step is to calculate the transfer of gamma-rays through the NSM ejecta. However, we omitted the detailed Monte Carlo calculation of the radiation transfer because the optical depth decreases rapidly after the merger event, by roughly $\propto \sqrt{t}$ (Li 2019); within the scope of our study at $t \gg 1$ yr, the optical depth is thin and negligible. Therefore, the degradation of the line profiles by Compton scattering is not included in our calculation, which would be dominant in only the very early phase. Note that the detailed calculations of the megaront-electron gamma-ray spectra from Galactic NSMs in the initial phase were performed by Wang et al. (2020, 2021) and gamma-rays from NSMs per $Y_e$ by Chen et al. (2021). In this step, we only apply the bulk Doppler-broadening effect caused by the expansion velocity $v(t)$. The thermal Doppler-broadening effect is ignored in this calculation because it is two or three orders of magnitude smaller than that from the expansion motion of the heavy elements in the $A = 50–200$ range. In reality, the line profile from the bulk Doppler effect becomes complicated due to the complex contributions of various velocity components, as has been observed in the X-ray lines from heavy elements in supernova (SN) remnants (Grefenstette et al. 2017; Kasuga et al. 2018). For simplicity, we applied the Gaussian distribution function for the line profile in the calculation. Of the various velocity elements in the remnant, we only applied single Gaussian broadening to the maximum velocity component, which we assume to be the forward shock motion. This was done to simulate the most robust case for considering the gamma-ray sensitivity. In our assumption, $v(t)$ starts from the initial value $v(0) = 0.3 \, c$, where $c$ is the speed of light, and evolves at a constant rate during the free expansion phase. During the Sedov–Taylor phase, $v(t)$ evolves as $v(t) \propto t^{0.7}$ (Taylor 1950), and then as $v(t) \propto t^{(3/5)}$ during the pressure-driven snowplow phase (McKee &...
We assume that the free expansion, Sedov–Taylor, and probability density function phases end at \( t = 10, 4.7 \times 10^3, \) and \( 1.65 \times 10^6 \) yr, respectively. The ages of these phase transitions may change by about one order of magnitude due to differences in density of the CSM, but this modification only affects the Doppler-broadening effect. It becomes negligible when compared with the typical energy resolutions of gamma-ray instruments for ages older than \( t \sim 10^6 \) yr, the range that lies within the scope of this study. Note that even at \( t = 10^6 \) yr, \( v(t) \) approaches \( \sim 20 \text{ km s}^{-1} \), which is about double the speed of sound for a typical CSM density of \( 0.01 \text{ cm}^{-3} \). The radius becomes \( \sim 100 \) pc. Finally, we get the gamma-ray spectra for NSMs at \( t \), accumulated from all of the \( r \)-process nuclei in the ejecta.

### 2.2. Gamma-Ray Emission and Evolution

From the numerical calculation described in Section 2.1, the gamma-ray spectra from \( t = 3–10^6 \) yr, under the assumption that the ejecta mass is \( M_\text{ej} = 0.01 M_\odot \) at \( d = 10 \) kpc, are summarized in Figures 4 and 5. As described in Section 1, we assume that all of the emissions from the NSM remnants are observable within the wider FOV; this is assumed to be larger than the object size, which becomes around 10 pc at \( t = 10^5 \) yr and expands into around 100 pc at \( t > 10^6 \) yr. The spectra contain many nuclear lines broadened by the Doppler effect. They appear to form a continuous spectrum in the early phase, but they become separated at ages older than \( 10^3 \) yr. Note that the gamma-ray data without the Doppler-broadening effect (the outputs from the second step of the calculation in Section 2.1) is provided as the numerical model for the XSPEC tool (Arnaud 1996) in the HEASoft package (Appendix).

To identify the gamma lines in the spectra, we check the most prominent lines in the gamma-ray spectra generated by a single \( Y_e \) condition. Table 1 lists the brightest lines shown for the nuclei in each \( Y_e \). Roughly speaking, the bright lines seen for objects of a younger age lie in the higher-energy gamma-ray band of the spectrum. Further details of the diagnostics will be discussed in Section 3.

### 3. Gamma-Ray Diagnostics of NSM Remnants

#### 3.1. Spectral Color Changes of NSM Remnants

Using the energy spectra of the NSM remnants (Figures 4 and 5), we first checked the properties of the spectral shapes from the hard X-ray to the soft gamma-ray bands. As shown in the normalized spectra plotted in Figure 6, the energy spectra roughly evolve from hard to soft slopes. Gamma-ray emission decreases rapidly leaving the hard X-ray emission in old age, as is indicated in Table 1. This phenomenon of gamma-rays is equivalent to the Sargent law for \( \beta \) decay. To see the evolution of the shape of the \( \gamma \)-ray spectra more quantitatively, we plotted the light curves of the gamma-ray flux in three bands: 70–200, 200–500, and 500–3000 keV, which cover multiple lines around 100 and 300 keV, and a prominent line around 700 keV, respectively. As indicated in the top panel of Figure 7, the flux in the higher-energy bands decreases more quickly than that in the low-energy bands. A decaying trend is also seen in the time dependency of the hardness ratio among these bands, as is indicated in the lower panel of Figure 7. The ratio drops dramatically at around 200–300 yr, indicating that the gamma-ray flux above the 500 keV band quickly decreases at this age. This phenomenon is primarily due to the decay of \( ^{125}\text{Sb} \) and \( ^{137}\text{mBa} \) listed in Table 1. Note that this result does not change even if we adopt other \( Y_e \)-fraction models of DD2-125145, DD2-135135, SFHo-125145, and SFHo-135135 in Kullmann et al. (2022), as shown in Figure 7.

To compare the spectral shape of NSM remnants with other astronomical objects, we plotted the color–color diagrams in the hard X-ray band (10–500 keV) and in the hard X-ray to \( \gamma \)-ray band (70–3000 keV), in the top and bottom of Figure 8, respectively. We divided the energy bandpass for these spectra into three ranges: 10–25, 25–70, and 70–500 keV for the hard X-ray band (top of Figure 8), and 70–500, 500–1000, and 1000–3000 keV for the hard X-ray to gamma-ray band (Figure 8 bottom). Note that the divisions of the energy bands are defined so that they follow the energy bandpass of current gamma-ray instruments on board NuSTAR (Harrison et al. 2013), INTEGRAL (Winkler et al. 2003), and other observatories. For comparison, the spectral colors of other astronomical objects, calculated using the INTEGRAL catalog version 00438, are also plotted in the same figures. In the hard X-ray band (the 10–500 keV band in the top of Figure 8), the spectra of NSM remnants older than \( t \sim 1000 \) yr have spectral colors similar to those of SN remnants or active galactic nuclei, but NSM remnants younger than \( t \sim 1000 \) yr can be distinguished from other known objects by their hard X-ray colors. In other words, the spectral color in the hard X-ray band below 500 keV is a good indicator of young NSM remnants. Furthermore, this differentiation from known objects becomes more prominent when we include the higher-energy band covering the megaelectronvolt portion of the spectrum, as is clearly indicated in the bottom of Figure 8. Note that this result does not change even if we adopt other \( Y_e \)-fraction models of DD2-125145, DD2-135135, SFHo-125145, and SFHo-135135 in Kullmann et al. (2022), as shown in Figure 8. Therefore, NSM remnants have unique spectral colors in the hard X-ray to gamma-ray bands. This observation is one of the important conclusions drawn from our calculation. Note that the spectral models in the INTEGRAL catalog are simple enough that the colors of known objects in the gamma-ray band (bottom of Figure 8) are less scattered than those in the hard X-ray band (top of Figure 8). The spectral separation between NSM remnants and other objects in the bottom of Figure 8 does not change dramatically, even if we lower the low-energy threshold (70 keV in the bottom of Figure 8) to cover 20 keV, for example. However, it becomes worse if we set it higher so that everything up to a certain point; 200 keV, for example, is ignored. This implies that hard X-rays around 100 keV provide key information for distinguishing NSM remnants from other objects. Note that these results are based on the pure-nuclear gamma-rays from \( r \)-process nuclei in NSMs, and thus the synchrotron radiation from electrons that are accelerated by the shocks may contaminate the hard X-ray band for young remnants. Additionally, when taking actual observations, we must be careful to isolate the contamination of the hard X-ray spectrum that arises from other objects located behind the NSM, such as active galactic nuclei within the FOV.

#### 3.2. Nuclear Line Emissions from Older NSM Remnants

For ages older than \( t > 3000 \) yr, nuclear lines are clearly seen in the gamma-ray spectra of NSM remnants due to the minimal

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8. https://www.isdc.unige.ch/integral/science/catalogue
Doppler-broadening effect, as is shown in Figures 4 and 5. Using the gamma-ray spectra of NSM remnants that were shown in Section 2 (i.e., the $Y_e$ distribution for the NSM case with $M_{ej} = 0.01 M_\odot$ at $d = 10$ kpc), we selected the brightest nuclear lines in each energy band, 3–75, 75–500, and 500–4000 keV, for at least one epoch in the age range spanning $t = 10^4 \times 10^6$ yr. Note that these energy bands are defined such that they simulate the energy bands that are observable by current and near-future

Figure 4. Gamma-ray spectra simulated for the NSM case at $t = 3 \times 10^3$ yr, assuming a distance of 10 kpc with an initial velocity of 0.3 $c$ (see the text). The red and black plots represent the spectra with and without the Doppler-broadening effect, respectively. The time since the merging event and the velocities are shown in each top label. The simulated spectra are available as data behind the figure in the table spectral model for XSPEC.

(The data used to create this figure are available.)
instruments aboard satellites, such as the hard X-ray focusing missions NuSTAR (Harrison et al. 2013) and FORCE (Nakazawa et al. 2018), and gamma-ray missions like INTEGRAL (Winkler et al. 2003), e-ASTROGAM (De Angelis et al. 2017; De Angelis et al. 2018), AMEGO (Kierans 2020), and GRAMS (Aramaki et al. 2020).

Figure 9 presents the time evolution of the brightest nuclear gamma-ray lines in these energy bands. To account for the reduction in the line sensitivities as a result of the Doppler-broadening effect, we accumulated the photons that were within the energy resolution of $\Delta E = 3 \pm 1$ keV from the center of energy of their associated lines. This chosen value for the energy resolution is typical for semiconductor gamma-ray detectors. For reference, the evolution of lines without Doppler broadening is also shown in the figure as dashed lines. As indicated in Figure 9, the Doppler-broadening effect becomes
less dominant in the hard X-ray band after a few hundred years, but it is still present until about \( t = 10^3 \) yr and \( t = 10^4 \) yr in the soft gamma-ray and the hard gamma-ray bands, respectively. Note that the reason why several lines, such as those of \( ^{126}\text{Sb} \) and \( ^{239}\text{Np} \), increase as \( t \) approaches \( 10^3-10^5 \) yr is that the number of parent nuclei increases in these phases. From Figure 9, we can identify the nuclear lines that are useful as indicators for the ages of NSMs. The ages can be categorized into three epochs: \( t < 100 \), \( t \sim 10^3-10^4 \), and \( t > 10^4 \) yr. In summary, if we detect the lines from \( ^{125}\text{Sb}, ^{194}\text{Os}, ^{227}\text{Th}, \) or \( ^{194}\text{Ir} \), then we can determine the age of the NSM to be very young at \( t < 100 \) yr. Similarly, lines from \( ^{137}\text{mBa} \) in the gamma-ray band indicate that the age is around \( t \sim 10^2 \) yr. In the age range spanning \( t \sim 10^3-10^4 \) yr, nuclear lines will be detected from \( ^{140}\text{Am}, ^{241}\text{Am}, ^{214}\text{Pb}, ^{228}\text{Np}, \) and/or \( ^{214}\text{Bi} \). A nuclear line from \( ^{126}\text{mSn} \) indicates that the NSM is very old at \( t > 10^3 \) yr. In the wide age range from \( t = 400-10^4 \) yr, the line from \( ^{128}\text{Sn} \) stays almost constant at \( 10^{-9} \) photons \( \text{s}^{-1} \text{cm}^{-2} \) for a distance of \( d = 10 \) kpc, and thus it can be used as a standard candle for measuring \( d \).

### 3.3. Line Diagnostics for the Electron Fraction

In addition to the spectral colors (Section 3.1), nuclear lines can be used to identify NSM remnants among astronomical objects, especially when the remnants are of an older age. Since the NSMs are thought to have both a more neutron-rich environment and a lower \( Y_e \) condition than SNe (Lattimer & Schramm 1974; Metzger et al. 2010; Wanajo et al. 2011), a new line-diagnostic method utilizing \( Y_e \) values will be useful for distinguishing NSMs from SNe. In this subsection, we search for gamma-ray line diagnostics for \( Y_e \). We use the gamma-ray spectra calculated under the pure \( Y_e \) conditions in the \( Y_e = 0.10-0.45 \) range, whereas in the previous sections we used the mixed \( Y_e \) condition for NSMs. To identify the best candidates among the nuclear gamma-ray lines for the identification of \( Y_e \), we first selected the five brightest lines for each age, \( t = 100, 1000, 10^5, 10^6 \), and \( 10^6 \) yr, and for each \( Y_e \) \((0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, \) and \( 0.45) \). Then among these 5 \((5 \times 5 = 25) \) \( Y_e \) lines, we
selected the nuclear lines that appeared in two or more of the conditions for $t$ and $Y_e$. In total, 10 gamma-ray lines are selected and are marked as $\dagger$ and $\ddagger$ in Table 1 for $t < 100$ and $t > 100$ yr, respectively. Therefore, the lines from $^{137m}$Ba (661.7 keV), $^{85}$Kr (513.9 keV), and $^{125}$Sb (427.9 keV) in ages below 100 yr are indicators of low-, middle-, and high-$Y_e$ environments, respectively. Here, low, middle, and high are numerically defined as $Y_e \sim 0.10$–0.20, 0.20–0.35, and 0.35–0.45, respectively. In ages older than $t = 100$ yr, the lines from $^{225}$Ra (40.0 keV), $^{243}$Am (74.7 keV), $^{239}$Np (106.1 keV), $^{213}$Bi (440.5 keV), and $^{214}$Bi (609.3 keV) are emitted from a low-$Y_e$ environment, whereas the lines from $^{60m}$Co (58.6 keV) and $^{126}$Sn (87.6 keV) become bright in the middle- and high-$Y_e$ environments, respectively.

The Astrophysical Journal, 933:111 (13pp), 2022 July 1

Since the absolute flux of a single line changes with respect to $t$ and $d$, the ratio between two or more lines should be a good indicator of $Y_e$. Figure 10 summarizes the line intensities and their ratios using the 10 nuclei selected above. For simplicity, the plots for young and old ages, $t = 10^{-3}$ and $10^{3}$–$10^{6}$ yr, respectively, are shown separately. In the young age range (top of Figure 10), the ratios of $^{137m}$Ba/$^{85}$Kr, $^{125}$Sb/$^{137m}$Ba, and $^{85}$Kr/$^{125}$Sb become larger than unity in the low-, middle-, and high-$Y_e$ environments, respectively. These low- and high-$Y_e$ indicators (i.e., $^{137m}$Ba/$^{85}$Kr and $^{85}$Kr/$^{125}$Sb, respectively) exhibit more prominent ratios over time since $^{85}$Kr decays slower than $^{125}$Sb and faster than $^{137m}$Ba, whereas the middle indicator ($^{125}$Sb/$^{137m}$Ba) becomes dim after 100 yr. Note that the plots use the incident line fluxes calculated in step 2 in Section 2.1, and the reduction due to the Doppler-broadening effect is not considered. The Doppler effect is particularly significant in plots for the young age range (top of Figure 10). Quantitatively, the ratios of $^{137m}$Ba/$^{85}$Kr, $^{125}$Sb/$^{137m}$Ba, and $^{85}$Kr/$^{125}$Sb change by factors of 1.57, 0.82, and 0.77, respectively, for $t < 1,000$ yr. In the old age range (middle of Figure 10), the ratios of $^{243}$Am/$^{60m}$Co, $^{126}$Sn/$^{243}$Am, and $^{60m}$Co/$^{126}$Sn indicate the low-, middle-, and high-$Y_e$ environments, respectively. The line from $^{239}$Np has the same flux and time evolution as that from $^{243}$Am (red plots) because they are in the same decay chain. Similarly, the lines from $^{214}$Bi, $^{225}$Ra, and $^{213}$Bi (green plots) follow almost the same trend as those from $^{243}$Am and $^{239}$Np (red plots). Among them, the low-$Y_e$ indicator ($^{243}$Am/$^{60m}$Co) in the old age range is valid up to $t = 10^{3}$ yr, and the middle-$Y_e$ indicator ($^{126}$Sn/$^{243}$Am) shows more significant ratios with $t > 10^{3}$ yr. On the other hand, lines for the high-$Y_e$ indicator $^{60m}$Co/$^{126}$Sn decay quickly and become unavailable after $10^{7}$ yr; that is, if the ratio $^{60m}$Co/$^{126}$Sn is larger than unity, then the object is in a high-$Y_e$ environment with an age of $t \sim 10^{7}$ yr. In summary, using these indicators, which become larger than unity in specific $Y_e$ conditions, we can estimate the $Y_e$ environment independently from the spectral color diagnostics shown in Section 3.1.

Finally, we checked the line ratios blended by $Y_e$ distributions of the NSM cases. The time evolution is plotted in Figure 10 (bottom). The difference in the $Y_e$-fraction models between Wanajo et al. (2014) and Kullmann et al. (2022) does not affect the trend of the NSMs very much. These gamma-ray lines are also expected to be observed from the remnants of core-collapse SNe, which are considered to be less neutron-rich environment at $Y_e \sim 0.5$ (Andres et al. 2020) than NSMs. However, our numerical calculation model in this paper has limitations in estimating gamma-ray radiation from the core-collapse SNe because the mass fractions of the $r$-process nuclei in the ejecta are different between the maximum $Y_e$ condition of our calculation (i.e., $Y_e = 0.45$) and the SN ejecta case ($Y_e \sim 0.50$), and the neutron-rich nuclei in the nominal core-collapse SNe are predominantly generated via the $s$-process rather than the $r$-process. For reference, we plotted the time evolution of the line ratios in the gamma-ray spectra of $Y_e = 0.45$, which should still reproduce well in an environment with almost-equal numbers of neutrons and protons. According to Figure 10 (bottom), we expect the low-$Y_e$ indicators (i.e., $^{137m}$Ba/$^{85}$Kr and $^{243}$Am/$^{60m}$Co) in the NSM case to become many orders of magnitude larger than those in the SNe case. In the core-collapse SNe where neutron-rich nuclei are generated via the $s$-process, a relatively large amount of $^{85}$Kr and almost no $^{243}$Am are synthesized. Therefore, the difference in these low-$Y_e$ indicators between the NSMs and SNe cases is expected to...
become larger than those shown in Figure 10 (bottom). As for the middle-$Y_e$ indicators ($^{125}$Sb/$^{137m}$Ba and $^{126}$Sn/$^{243}$Am), they may not be useful in distinguishing gamma-rays from NSMs and SNe according to Figure 10 (bottom). In the $s$-process environment of core-collapse SNe, almost no $^{137m}$Ba and $^{243}$Am are synthesized and thus these middle-$Y_e$ indicators can be larger than the values in the figure. Finally, the high-$Y_e$ indicators ($^{85}$Kr/$^{125}$Sb and $^{60m}$Co/$^{126}$Sn) can discard the NSMs from the SNe cases as indicated in Figure 10 (bottom). In summary, the new line diagnostic method for $Y_e$ provides a tool for distinguishing between NSMs and SNe.

**4. Discussion**

In Section 2, we presented a nuclear-decay simulation using a large nuclear database, the goal of which was to estimate the gamma-ray spectra of NSMs up to the age of $t = 10^6$ yr. We have identified many nuclear lines, listed in Table 1, that can be used for identifying the nucleosynthesis environments of NSMs, even with the Doppler-broadening effect altering the profiles of these lines in the young age range. In Section 3, we numerically analyzed the simulated gamma-ray spectra from NSMs and found that the spectral slope in the soft gamma-ray band above 500 keV changes at around $t = 200–300$ yr. We also found that the spectral colors of NSMs in the hard X-ray to soft gamma-ray bands differ from those of other astronomical objects up to $t = 10^5$ yr old. Consequently, we can identify a gamma-ray object as an NSM remnant using the gamma-ray spectral colors (Section 3.1). Among the many nuclear lines in the spectra, we identified that the nuclear lines from $^{241}$Am, $^{243}$Am, $^{214}$Pb, $^{239}$Np, and $^{214}$Bi are prominent for $t = 10^3–10^4$ yr, and that the lines from $^{126}$Sn and $^{126m}$Sb are prominent for $t > 10^4$ yr (Section 3.2). In addition, we proposed a new line diagnostic method for distinguishing $Y_e$ environments that use the line ratios of $^{137m}$Ba/$^{85}$K and $^{244}$Am/$^{60m}$Co, which become larger than unity for low-$Y_e$ objects with young and old ages, respectively (Section 3.3). This diagnostic method distinguishes NSMs from SNe. In the next section, we focus on the sensitivities in the gamma-ray band that are required for current and future megelectronvolt gamma-ray missions that aim to search for Galactic NSM remnants.

**4.1. Detectable Distance to Galactic NSM Remnants**

A gamma-ray flux from the brightest line in a particular age range can be used to estimate the distance that a virtual...
The ratios in the lower panel between $^{243}$Am and $^{60}$mCo, between $^{214}$Bi and $^{85}$Kr, $^{125}$Sb and $^{137}$mBa, and $^{85}$Kr and $^{125}$Sb are shown in purple, orange, and cyan, respectively. The NSM case by the mass fraction of Wanajo shown by the thin purple, thin orange, thin cyan, thick purple, thick orange, and thick cyan lines, respectively. Among the lines are plotted in the lower panel; the ratios between $^{137}$mBa and $^{85}$Kr, $^{125}$Sb and $^{137}$mBa, and $^{85}$Kr and $^{125}$Sb are shown in red, black, and blue, respectively. Thick, dotted, and dashed lines represent the intensities at $t > 100$ yr, respectively. (Middle) Same plot as the top panel but for older ages ($t > 100$ yr), $\tau$ marks in Table 1. The dependencies of $^{243}$Am (and $^{249}$Np), $^{214}$Bi (and $^{229}$Ra, $^{213}$Bi), $^{60}$mCo, and $^{126}$Sn are shown in red, green, black, and blue, respectively, and the thick, dotted, dashed, and dotted dash lines represent the intensity at $t = 10^3$, $10^5$, $10^7$, and $10^9$ yr, respectively, in the upper panel. The ratios in the lower panel between $^{243}$Am and $^{60}$mCo, between $^{214}$Bi and $^{60}$mCo, between $^{126}$Sn and $^{243}$Am, between $^{125}$Sb and $^{214}$Bi, and between $^{60}$mCo and $^{126}$Sn are shown in purple, brown, orange, dark yellow, and cyan, respectively. (Bottom) The time dependencies of the line ratios of $^{157}$mBa $^{85}$Kr, $^{125}$Sb, $^{137}$mBa, $^{85}$Kr, $^{125}$Sb, $^{137}$mBa, $^{125}$Sb, $^{137}$mBa, $^{60}$mCo, $^{126}$Sn, and $^{60}$mCo $^{126}$Sn are shown by the thin purple, thin orange, thin cyan, thick purple, thick orange, and thin cyan lines, respectively. The NSM case by the mass fraction of Wanajo et al. (2014) and the case of $Y_e = 0.45$ are shown by the straight and dotted lines, respectively. The results of the other NSM models, DD2-125145, DD2-135135, SFHo-125145, and SFHo-135135 in Kullmann et al. (2022), are shown in the lighter colors.

Figure 11 summarizes the achievable limit of $d$ for NSM remnants as a function of $t$ and is calculated for the three energy bands 3–75, 75–500, and 500–4000 keV. For example, instruments with a line sensitivity of $10^{-7}$ photons s$^{-1}$ cm$^{-2}$ in the 3–75 keV band (red line at the top of Figure 11), such as Hitomi HXI (Takahashi et al. 2014) and NuSTAR (Harrison et al. 2013), can observe the brightest lines from NSM remnants with $t < 10^3$ yr at $d = 3$ kpc. We also checked the degradation of the distance limit due to the Doppler-broadening effect, as shown in the middle of Figure 11, but the results do not dramatically change. If the line sensitivities are the same among the three energy bands, then hard X-rays (thick lines) will be a powerful tool in the search for NSMs that are younger than $t < 10^3$ yr, but the gamma-ray observations (dotted or dashed lines) are better for surveying NSMs that are older than $t > 10^3$ yr.

The G4.8+6.2 associated with AD 1163 is one example, from the middle of Figure 11, that provides the requirement for the gamma-ray sensitivity needed to observe an NSM remnant with a known distance and age. The object is reported to be a young kilonova remnant with $t \sim 860$ yr (Liu et al. 2019). If it is an NSM remnant at $d \sim 10$ kpc, then a sensitivity of $10^{-8}$ and $10^{-9}$ photons s$^{-1}$ cm$^{-2}$ is required to observe G4.8+6.2 in the hard X-ray and gamma-ray bands, respectively. This sensitivity is roughly one or two (or more) orders of magnitude deeper than that of INTEGRAL IBIS (Winkler et al. 2003). If the distance is closer at $d \sim 3$ kpc, then hard X-ray instruments with a sensitivity of $10^{-7}$ photons s$^{-1}$ cm$^{-2}$ in the 3–75 keV band, such as Hitomi HXI (Takahashi et al. 2014) and NuSTAR (Harrison et al. 2013), are expected to be able to observe the emissions from the object.

4.2. Direct Estimation of Local NSM Rates Using Gamma-Rays

To estimate the coverage of Galactic NSM remnants observable for specific gamma-ray sensitivities, we first prepare a probability map for the existence of Galactic NSMs. This is given in the same plane as the top and middle of Figure 11 (the $t$–$d$ plane). Since NSMs are not uniformly distributed in our Galaxy, we apply the probabilities for NSMs in the $d$ and $t$ spaces given by Wu et al. (2019) and multiply them to get the plot shown in the bottom of Figure 11. We assume that the NSMs are primarily concentrated around the Galactic plane. Most of the NSMs are expected to exist at around $d \sim 8$ kpc and $t \sim 10^3$–$10^4$ yr, as has already been described in Wu et al. (2019).

We then accumulate the probabilities for the existence of NSMs (bottom of Figure 11) within the distance-limit curves (top and middle of Figure 11). As a result, we obtained the coverage of Galactic NSMs as a function of the line sensitivity; this is shown at the top of Figure 12. For example, if we survey Galactic NSM remnants with an instrument having a line sensitivity of $10^{-8}$ photons s$^{-1}$ cm$^{-2}$ in the 3–75 keV band, then we expect to observe about 3% of the NSMs in our Galaxy with $M_{ej} = 0.01 M_\odot$. This value corresponds to about one object if we assume an NSM rate in our Galaxy of 30 per $10^6$ yr. In addition, we performed the same procedure to estimate the NSM coverage in units of erg per second per cubic centimeter, which requires a sensitivity that is $E_1^2$ times higher than that required for units of photons per second per cubic centimeter. Here, $E_1$ is the photon energy (the energy of the gamma-ray line). The results are shown in the bottom of Figure 12. Therefore, instruments that can achieve a sensitivity of $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ in the 75–500 or the 500–4000 keV bands are expected to be able to observe one NSM remnant.
with $M_{ej} = 0.01 M_\odot$ in our Galaxy under the same assumption of the NSM rate mentioned above. Similarly, a sensitivity of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ is required in the hard X-ray band to observe one object with the same $M_{ej}$.

The NSM rates from previous studies are summarized in Figure 13. The NSM rates are estimated using several methods, and even though the values approach each other recently, they still have non-negligible uncertainties or systematic errors that are dependent on the methods used. According to Figure 12, instruments with higher sensitivities can cover more than 10% of NSMs and should be able to observe multiple Galactic NSM remnants (meaning a sensitivity of $10^{-9.5}$–$10^{-8.5}$ photons s$^{-1}$ cm$^{-2}$ or $10^{-16.5}$–$10^{-14.5}$ erg s$^{-1}$ cm$^{-2}$ in the hard X-ray to gamma-ray bands). The actual numbers observed by future NSM surveys with highly sensitive instruments will provide direct information for the NSM rate in the local universe.

4.3. Sensitivity Requirements for Future Missions

To assess the feasibility of detecting Galactic NSM remnants using past, current, and future gamma-ray missions, the gamma-ray spectra expected from NSMs (Figures 4 and 5)
missions. Consequently, we conclude that future missions, such as e-ASTROGAM, AMEGO, and GRAMS, have the potential to detect megaelectronvolt emissions from young NSM remnants in the age range of $t = 100$–1000 yr old at 10 kpc, with a sensitivity of approximately $10^{-13}$–$10^{-11}$ erg cm$^{-2}$ s$^{-1}$. Furthermore, the hard X-ray band below 100 keV is also useful in searching for NSM remnants. NuSTAR data may be able to indicate very young NSM remnants at about $t = 100$ yr, and FORCE may be able to detect emissions from an NSM older than $t < 10^5$ yr at 10 kpc.

This work was supported in part by JSPS KAKENHI [Grant Nos. JP18H04571 and JP20K04009 (Y.T.), JP18H01232, andJP22H01251 (R.Y.), JP20K03957 (S.F.), JP20H00174 (S.K.), JP21H01121 (S.K., Y.T., S.F.), JP19K03908 (A.B.)]. Y.T. and S.K. are deeply appreciative of the Observational Astrophysics Institute at Saitama University for supporting the research fund, and R.Y. deeply appreciates the Aoyama Gakuin University Research Institute for helping to fund our research. Finally, we would like to thank the anonymous referee for his/her careful reading of our manuscript and helpful comments.

Facilities: INTEGRAL, CGRO, NuSTAR, Hitomi, Fermi, SMILE, GRAMS, AMEGO, e-ASTROGAM, FORCE

Appendix

XSPEC Model for Gamma-Rays from $r$-process Objects

The gamma-ray spectra for NS remnants in this paper are implemented as the table spectral model for XSPEC (Arnaud 1996) version 12 in the HEAsoft package. The model is provided with the file name of $rprocgamma.mod$ in the Flexible Image Transport System (FITS) format (Hanisch et al. 2001); the data file is available as the data behind Figures 4 and 5. The model parameters and descriptions are summarized below. The model does not contain the Doppler effect, but instead, it gives the output of the second step described in Section 2.1.

1. time: time from the merging event, in units of years.
2. $Y_{NN}$ ($NN = 10, 15, 20, 25, 30, 35, 40, 45$): the ejecta mass of the $r$-process nuclei in solar mass units $M_{\odot}$ under the $Y_{e} = 0.1N$ environment.
3. $z$: redshift
4. norm: normalization in units of photons s$^{-1}$ cm$^{-2}$ d$^{-2}$ (1 + $z$)$^{-2}$, where $d$ is the distance to the object in kpc.

For example, the spectral model of a Galactic NSM remnant at $t = 100.0$ yr and $d = 10$ kpc, calculated under the assumption that the ejecta masses of $Y_{e} = 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40,$ and 0.45 are 0.0454, 0.0485, 0.146, 0.297, 0.103, 0.251, 0.105, and 0.00326 $M_{\odot}$, respectively, without the Doppler-broadening effect, is described with the following parameters:

| Model Table[rprocgamma.mod]<1> Source No.: 1 Active/Off |
|----------------------------------------------------------|
| Model Model Component Parameter Unit Value               |
| par comp                                                |
| 1  rprocgamma time year 100.000 +/- 0.0                   |
| 2  rprocgamma Ye10 MSun 4.54000E-02 +/- 0.0               |
| 3  rprocgamma Ye15 MSun 4.85000E-02 +/- 0.0               |
| 4  rprocgamma Ye20 MSun 0.146000 +/- 0.0                  |
| 5  rprocgamma Ye25 MSun 0.297000 +/- 0.0                  |
| 6  rprocgamma Ye30 MSun 0.103000 +/- 0.0                  |
| 7  rprocgamma Ye35 MSun 0.251000 +/- 0.0                  |

...are compared with the sensitivities of the instruments for these missions in Figure 14. For the megaelectronvolt bands, we expect that in the 2030 s sensitivities will be achieved that are one or two orders of magnitude higher than those of current...
An example of the XSPEC commands to use this numerical model with the Doppler-broadening effect are the following. The command on the first line sets the model and parameters, and the second one changes the plot device. After setting a dummy response on the third line, we can plot the model on the screen using the command on the fourth line. For the details, please refer to the XSPEC manual.

```
XSPEC12 > model gsmooth(atable rprocgamma mod)
XSPEC12 > cpd/xw
XSPEC12 > dummyrsp 1 4000 1000
XSPEC12 > plot model
```

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