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SUPERNOVAE AS THE SITE OF THE *r*-PROCESS: IMPLICATIONS FOR GAMMA-RAY ASTRONOMY

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ABSTRACT

We discuss how detection of gamma-ray emission from the decay of *r*-process nuclei can improve our understanding of *r*-process nucleosynthesis. We find that a gamma-ray detector with a sensitivity of $\sim 10^{-7} \gamma$ cm^{-2} s^{-1} at $E_\gamma \approx$ 100–700 keV may detect the emission from the decay of ^{125}Sb, ^{137}Cs, ^{144}Ce, ^{155}Eu, and ^{194}Os produced in a future Galactic supernova. In addition, such a detector may determine the emission from the decay of ^{126}Sn in the Vela supernova remnant and the diffuse emission from the decay of ^{126}Sn produced by past supernovae in our Galaxy. The required detector sensitivity is similar to what is projected for the proposed Advanced Telescope for High Energy Nuclear Astrophysics (ATHENA). Both the detection of gamma-ray emission from the decay of several *r*-process nuclei (e.g., ^{125}Sb and ^{194}Os) produced in future Galactic supernovae and the detection of emission from the decay of ^{126}Sn in the Vela supernova remnant would prove that supernovae are a site of the *r*-process. Furthermore, the former detection would allow us to determine whether or not the *r*-process nuclei are produced in relative proportions specified by the solar *r*-process abundance pattern in supernova *r*-process events. Finally, detection of diffuse emission from the decay of ^{126}Sn in our Galaxy would eliminate neutron star–neutron star mergers as the main source for the *r*-process nuclei near mass number $A \sim 126$.

Subject headings: gamma rays: theory — nuclear reactions, nucleosynthesis, abundances — supernovae: general

1. INTRODUCTION

Approximately half of the natural abundance of heavy elements with mass number $A > 70$ and all of the actinides in the solar system came from the *r*-process. Although the *r*-process theory was put forward by Burbidge et al. (1957) and Cameron (1957) more than four decades ago, the site of the *r*-process has remained a mystery. The extreme conditions (e.g., neutron number densities exceeding $\sim 10^{20}$ cm^{-3} and timescales of ~ 1 s) required for the *r*-process suggest that it might occur in some violent astrophysical events such as core-collapse supernovae (i.e., Type II and Type Ib supernovae, hereafter referred to simply as supernovae). A similarly violent but more exotic site of the *r*-process might be neutron star–neutron star (NS-NS) mergers (see Cowan, Thielemann, & Truran 1991 for a review of the possible *r*-process sites).

Another question closely related to the site of the *r*-process concerns the relative production of *r*-process nuclei in individual events. Observation of *r*-process elements in extremely metal poor halo stars has shed some important light on this question. For example, Sneden et al. (1996) found that the *r*-process abundance pattern at and beyond Ba (i.e., at $A \geq 135$) in CS 22892−052 is consistent with that in the solar system. This suggests that the solar *r*-process abundance pattern, especially the part at $A \geq 135$, may be generic to the *r*-process and thus may characterize the production in every event. However, elements in the solar *r*-process abundance peak at $A \sim 130$ have not yet been detected in CS 22892−052. Furthermore, since it is difficult to establish that the *r*-process elements in this star were produced in a single event, the observed *r*-process abundance pattern could still be a superposition of those from (intrinsically) different events. Therefore, the relevance of the solar *r*-process abundance pattern to the production in individual events remains to be established.

In this paper we discuss how detection of gamma-ray emission from the decay of *r*-process nuclei may answer the following questions: (1) are supernovae a site of the *r*-process? (2) are the *r*-process nuclei produced in relative proportions specified by the solar *r*-process abundance pattern in supernova *r*-process events? and (3) are NS-NS mergers a main source for some *r*-process nuclei?

Gamma-ray emission characteristic of a radioactive nucleus from an astrophysical event would provide direct evidence for production of this nucleus in such an event. Clayton, Colgate, & Fishman (1969) predicted that such emission might be detectable. More recently, Meyer & Howard (1991) discussed possible gamma-ray signatures of an *r*-process event. In particular, with consideration of supernovae as the *r*-process site, they estimated gamma-ray fluxes from the decay of some *r*-process nuclei produced in SN 1987A. They also discussed the possibility of detecting such fluxes.

In the present work, we generalize the approach of Meyer & Howard (1991) with particular consideration given to future gamma-ray detectors. We find that if supernovae are the sites of the *r*-process, a number of *r*-process nuclei, namely ^{125}Sb, ^{137}Cs, ^{144}Ce, ^{155}Eu, and ^{194}Os, can provide gamma-ray fluxes of $\sim 10^{-7} \gamma$ cm^{-2} s^{-1} from a future Galactic supernova at a distance of 10 kpc. In addition, we show that the decay of ^{126}Sn in the Vela supernova remnant can produce fluxes of a similar magnitude. Detection of such fluxes would be possible for a gamma-ray detector with a sensitivity similar to what is projected for

TABLE 1

EXPECTED GAMMA-RAY FLUXES FROM A GALACTIC SUPERNOVA

Decay Chains of r-Process Nuclei	$X^{r}_{\odot}$ [a] ($\times 10^{-9}$)	δM [b] ($10^{-7}\ M_{\odot}$)	$\bar{\tau}$ [c] (yr)	E_{γ} (keV)	I_{γ}	F_{γ} [d] ($10^{-7}\gamma$ cm^{-2} s^{-1})
$^{125}Sb \rightarrow {}^{125}Te$	0.85	2.6	3.98	35.5	0.043	0.70
				176	0.068	1.1
				380	0.015	0.25
				428	0.296	4.8
				463	0.105	1.7
				601	0.179	2.9
				607	0.050	0.82
				636	0.113	1.8
				671	0.018	0.29
$^{137}Cs \rightarrow {}^{137}Ba$	0.26	0.77	43.4	662	0.851	0.35
$^{144}Ce \rightarrow {}^{144}Pr \rightarrow {}^{144}Nd$	0.44	1.3	1.12	80.1	0.014	0.35
				134	0.111	2.9
				697	0.013	0.35
				2186	0.007	0.18
$^{155}Eu \rightarrow {}^{155}Gd$	0.18	0.54	6.87	86.5	0.307	0.50
				105	0.212	0.34
$^{194}Os \rightarrow {}^{194}Ir \rightarrow {}^{194}Pt$	2.1	6.4	8.66	43.1	0.054	0.65
				294	0.026	0.31
				328	0.131	1.6
				645	0.012	0.14

[a] Solar r-process mass fractions of the stable nuclei in the decay chains.
[b] Amounts of production per supernova for the r-process nuclei at the beginning of the decay chains estimated from eq. (1) with $M_{G} = 10^{11}\ M_{\odot}$, $t_{G} = 10^{10}$ yr, and $f_{SN} = (30\ \mathrm{yr})^{-1}$.
[c] Lifetimes of the r-process nuclei at the beginning of the decay chains.
[d] Gamma-ray fluxes estimated from eq. (2) for a supernova at a distance of 10 kpc.

the proposed Advanced Telescope for High Energy Nuclear Astrophysics (ATHENA) (Kurfess 1994). Such an instrument may also detect the diffuse gamma-ray emission from the decay of ^{126}Sn produced by past supernovae in the Galaxy. Both the detection of gamma-ray emission from the decay of several r-process nuclei (e.g., ^{125}Sb and ^{194}Os) produced in future Galactic supernovae and the detection of emission from the decay of ^{126}Sn in the Vela supernova remnant would prove that supernovae are a site of the r-process, thus answering the first question posed above. In addition, the former detection would allow us to determine whether or not the r-process nuclei are produced in relative proportions specified by the solar r-process abundance pattern in supernova r-process events, thus answering the second question. The third question would be answered by detection of diffuse gamma-ray emission from the decay of ^{126}Sn in the Galaxy, since this detection would eliminate NS-NS mergers as the main source for the r-process nuclei near $A \sim 126$.

In § 2 we estimate gamma-ray fluxes from the decay of a number of r-process nuclei (e.g., ^{125}Sb and ^{194}Os) produced in a future Galactic supernova and from the decay of ^{126}Sn in the Vela supernova remnant. Diffuse fluxes from the decay of ^{126}Sn produced by past supernovae in the Galaxy are also estimated. In § 3 we discuss the results of § 2 in connection with answers to the three questions posed above. We give our conclusions in § 4.

2. GAMMA-RAY EMISSION FROM THE DECAY OF r-PROCESS NUCLEI

In this section, we assume that supernovae are the site of the r-process. Gamma-ray emission from the decay of nuclei produced in a supernova may be detected only after it becomes transparent to gamma rays. In the case of Type II supernovae, the delay between the explosion and onset of gamma-ray transparency is typically several years. This delay is shorter if strong mixing occurs in the envelope, such as for SN 1987A (see, e.g., Arnett et al. 1989), or if the supernova progenitor does not have a hydrogen envelope (e.g., Type Ib supernovae). Unambiguously, r-process nuclei that may be of interest to gamma-ray astronomy must have lifetimes of ~ 1 yr or longer. A search through the Table of Isotopes (Firestone et al. 1996) identifies seven such nuclei. The five relatively short-lived ones are ^{125}Sb, ^{137}Cs, ^{144}Ce, ^{155}Eu, and ^{194}Os (see Table 1), and the two long-lived ones are ^{126}Sn (see Table 2) and ^{182}Hf. We emphasize that all of these nuclei are bypassed by the s-process and are made only in the r-process.

2.1. *The Relatively Short-lived r-Process Nuclei*

Lifetimes of the five relatively short-lived r-process nuclei range from 1.12 yr for ^{144}Ce to 43.4 yr for ^{137}Cs (see Table 1). Since these lifetimes are shorter than or comparable to the average interval (~ 30 yr) between successive super-

TABLE 2

EXPECTED GAMMA-RAY FLUXES FROM THE DECAY OF ^{126}SN[a]

E_{γ} (keV)	I_{γ}	F_{γ} (Vela)[b] ($10^{-7}\gamma$ cm^{-2} s^{-1})	$\mathcal{F}_{\gamma}$ (diffuse)[c] ($10^{-7}\gamma$ cm^{-2} s^{-1} rad^{-1})
23.3......	0.064	0.14	0.32
64.3......	0.096	0.21	0.48
86.9......	0.089	0.19	0.44
87.6......	0.370	0.80	1.8
415	0.976	2.1	4.9
666	0.999	2.2	5.0
695	0.965	2.1	4.8
721	0.075	0.16	0.37

[a] The lifetime of ^{126}Sn is 1.14×10^{5} yr. The decay chain is $^{126}Sn \rightarrow {}^{126}Sb \rightarrow {}^{126}Te$.
[b] Gamma-ray fluxes from the Vela supernova remnant, taken to be at a distance of 200 pc and having $5.0 \times 10^{-7}\ M_{\odot}$ of ^{126}Sn; see eq. (3).
[c] Diffuse gamma-ray fluxes in the Galactic center direction for a uniform ^{126}Sn production rate of $p = 1.65 \times 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$ in the Galaxy; see eq. (7).

novae in the Galaxy, one has to wait for a future Galactic supernova to detect the gamma-ray emission from the decay of these nuclei.

These five relatively short-lived *r*-process nuclei were also identified by Meyer & Howard (1991), as well as ^{90}Sr, ^{106}Ru, ^{151}Sm, and ^{171}Tm. We do not include ^{90}Sr, ^{151}Sm, and ^{171}Tm in our discussion since fluxes from their decay are much lower than those from the decay of the other relatively short-lived *r*-process nuclei. Furthermore, ^{90}Sr and ^{106}Ru are commonly produced in the α-process (Woosley & Hoffman 1992), and thus cannot provide signatures unique to the *r*-process. (In fact, observation by Sneden et al. 1998 has shown that abundances of Sr, Y, and Zr with $A \sim 90$ in very metal-poor halo stars do not fit the solar *r*-process abundance pattern, whereas those elements which include Ba and beyond do fit the pattern.) Therefore, detection of gamma-ray emission from the decay of ^{106}Ru would not directly improve our understanding of *r*-process nucleosynthesis in contrast to the case of pure *r*-process nuclei.

Assuming that the solar *r*-process composition represents the Galactic average, we can estimate the average amount of mass in a radioactive *r*-process nucleus produced in a supernova as

$$\delta M \approx \frac{X^r_\odot M_G}{f_{SN} t_G} = 3 \times 10^{-7}\ M_\odot \left(\frac{X^r_\odot}{10^{-9}}\right)\left(\frac{M_G}{10^{11}\ M_\odot}\right) \times \left(\frac{10^{10}\ \text{yr}}{t_G}\right)\left(\frac{f_{SN}^{-1}}{30\ \text{yr}}\right), \quad (1)$$

where $X^r_\odot$ is the solar *r*-process mass fraction of the stable decay product of this nucleus (e.g., for ^{125}Sb, $X^r_\odot$ is from ^{125}Te), M_G and t_G are the total mass and the age of the Galaxy, respectively, and f_{SN} is the frequency within the Galaxy for the supernovae that produce this nucleus. We calculate $X^r_\odot$ in equation (1) for any specific nucleus from its solar mass fraction given by Arnett (1996) and the corresponding solar *r*-process fraction given by Käppeler, Beer, & Wisshak (1989). Subtraction of the *s*-process contribution in deriving the solar *r*-process fraction gives rise to a typical relative uncertainty of $\sim \pm 10\%$ in $X^r_\odot$. An exception is ^{137}Ba, with a relative uncertainty of $\sim \pm 100\%$ in $X^r_\odot$ (i.e., in the extreme case, there is no *r*-process production of the corresponding radioactive progenitor ^{137}Cs). As discussed in § 3, the largest uncertainty in δM comes from the intrinsic variation of the amount of *r*-process production in individual supernovae. So the value of δM in equation (1) should be taken as a rough estimate for production in a specific supernova.

If we assume that the delay between production of the *r*-process nucleus and onset of gamma-ray transparency of the supernova is small compared with the lifetime of this nucleus, then the gamma-ray flux to be detected from its decay is

$$F_\gamma = \frac{N_A}{4\pi d^2} \frac{\delta M}{A} \frac{I_\gamma}{\bar{\tau}} = 3.2 \times 10^{-6} I_\gamma \left(\frac{\delta M}{10^{-7}\ M_\odot}\right) \times \left(\frac{100}{A}\right)\left(\frac{1\ \text{yr}}{\bar{\tau}}\right)\left(\frac{10\ \text{kpc}}{d}\right)^2 \gamma\ \text{cm}^{-2}\ \text{s}^{-1}, \quad (2)$$

where d is the distance to the supernova, N_A is Avogadro's number, A is the mass number of this nucleus, $\bar{\tau}$ is its lifetime, and I_γ is the number of photons emitted at a specific energy E_γ per decay of this nucleus. The expected gamma-ray fluxes from the decay of the five relatively short-lived *r*-process nuclei are given in Table 1 for a supernova at a distance of 10 kpc, along with the expected mass δM in the corresponding nuclei produced in the supernova. These fluxes differ somewhat from the results (scaled to a distance of 10 kpc) of Meyer & Howard (1991) because they used somewhat different estimates of the *r*-process production δM and, apparently, different nuclear parameters in some cases.

2.2. *The Long-lived r-Process Nuclei*

The nucleus ^{126}Sn ($\bar{\tau} = 1.44 \times 10^5$ yr) can decay to both the ground and the first excited states of ^{126}Sb, which in turn decay to the stable ^{126}Te with lifetimes of 18 days and 27.6 minutes, respectively. Three prominent gamma rays at $E_\gamma = 415$, 666, and 695 keV are emitted with $I_\gamma \approx 1$ in the decay chain $^{126}\text{Sn} \rightarrow {}^{126}\text{Sb} \rightarrow {}^{126}\text{Te}$. Because of the long lifetime of ^{126}Sn, substantial gamma-ray fluxes are expected only from a nearby supernova (see eq. [2]). If we choose a reference value of $d = 200$ pc for the distance to the supernova, the corresponding flux from the decay of ^{126}Sn is

$$F_\gamma \approx 2.2 \times 10^{-7} I_\gamma \left(\frac{\delta M}{5 \times 10^{-7}\ M_\odot}\right)\left(\frac{200\ \text{pc}}{d}\right)^2 \gamma\ \text{cm}^{-2}\ \text{s}^{-1}. \quad (3)$$

In equation (3), the reference value of $\delta M = 5 \times 10^{-7}\ M_\odot$ for the amount of ^{126}Sn production is estimated from equation (1) with $X^r_\odot(^{126}\text{Te}) = 1.65 \times 10^{-9}$, $M_G = 10^{11}\ M_\odot$, $t_G = 10^{10}$ yr, and $f_{SN} = (30\ \text{yr})^{-1}$.

Interestingly, the distance to the Vela pulsar is estimated to be only about 125–500 pc (Milne 1968; Oberlack et al. 1994; Aschenbach, Egger, & Trümper 1995; Becker 1995). Furthermore, its age is estimated to be about 10^4 yr, much less than the lifetime of ^{126}Sn. Therefore, if the supernova associated with the Vela pulsar produced ^{126}Sn, then most of the radioactive ^{126}Sn nuclei initially produced in the supernova will remain there for a very long time. The expected gamma-ray fluxes from the decay of ^{126}Sn in the Vela supernova remnant are given in Table 2 for $d = 200$ pc (see Oberlack et al. 1994) and $\delta M = 5 \times 10^{-7}\ M_\odot$. (We note that gamma-ray emission from the decay of ^{26}Al has been detected from the Vela region; Diehl et al. 1995. In addition, an optical search for some *r*-process elements in the Vela supernova remnant was carried out by Wallerstein et al. 1995.)

For an *r*-process nucleus such as ^{126}Sn with $f_{SN}^{-1} \ll \bar{\tau} \ll t_G$, production by past supernovae that occurred over a long timescale can provide a substantial abundance of this nucleus in the Galaxy and therefore can give rise to diffuse gamma-ray emission. By "diffuse" we mean that the emission comes from a collection of unresolved point sources. Under the assumption that such a nucleus was uniformly produced over the Galactic history, its present abundance is

$$N \approx N_A \frac{p\bar{\tau}}{A}, \quad (4)$$

where

$$p \approx \frac{X^r_\odot M_G}{t_G} = 10^{-8}\left(\frac{X^r_\odot}{10^{-9}}\right)\left(\frac{M_G}{10^{11}\ M_\odot}\right)\left(\frac{10^{10}\ \text{yr}}{t_G}\right) M_\odot\ \text{yr}^{-1} \quad (5)$$

is its rate of production by mass in the Galaxy. Since we have taken $f_{\rm SN}^{-1} \ll \bar{\tau}$, there would have been a large number of supernova contributions to the diffuse emission that can be distributed quite irregularly through the Galaxy. In fact, diffuse emission from the decay of ^{26}Al predicted by Ramaty & Lingenfelter (1977) has been observed to be irregular (see Prantzos & Diehl 1996 for a review). If the Galactic distribution of a radioactive r-process nucleus is roughly the same as that of interstellar hydrogen (such a distribution is also consistent with that deduced for supernova remnants and pulsars), then according to Mahoney et al. (1982), the corresponding average diffuse flux at longitudes within $\pm 30°$ of the Galactic center is

$$\mathscr{F}_\gamma \approx 1.0 \times 10^{-46} N_{\rm A} \frac{p}{A} I_\gamma = 3.8 \times 10^{-7} I_\gamma \times \left(\frac{p}{10^{-8}\ M_\odot\ {\rm yr}^{-1}}\right)\left(\frac{100}{A}\right) \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm rad}^{-1}\ . \quad (6)$$

The "rad" in the unit for $\mathscr{F}_\gamma$ refers to the Galactic longitude. Note that $\mathscr{F}_\gamma$ is independent of $\bar{\tau}$ for $f_{\rm SN}^{-1} \ll \bar{\tau} \ll t_{\rm G}$.

From equation (6), the average diffuse flux from the decay of ^{126}Sn in the Galactic center direction is

$$\mathscr{F}_\gamma \approx 5.0 \times 10^{-7} I_\gamma \left(\frac{p}{1.65 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}}\right) \times \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm rad}^{-1}\ . \quad (7)$$

In equation (7), the reference value of $p = 1.65 \times 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ is estimated from equation (5) with $X^r_\odot(^{126}{\rm Te}) = 1.65 \times 10^{-9}$, $M_{\rm G} = 10^{11}\ M_\odot$, and $t_{\rm G} = 10^{10}$ yr. The diffuse fluxes from the decay of ^{126}Sn are also given in Table 2.

Similar calculations for ^{182}Hf [$\bar{\tau} = 1.3 \times 10^7$ yr and $X^r_\odot(^{182}{\rm W}) = 5.3 \times 10^{-11}$] show that although many gamma rays are emitted in the decay chain $^{182}{\rm Hf} \to {}^{182}{\rm Ta} \to {}^{182}{\rm W}$, the flux from the Vela supernova remnant is only $F_\gamma \sim 4.3 \times 10^{-11}\ \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}$, and the diffuse flux in the Galactic center direction is only $\mathscr{F}_\gamma \sim 8.9 \times 10^{-9}\ \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}\ {\rm rad}^{-1}$ for the most prominent line at $E_\gamma = 270$ keV with $I_\gamma = 0.8$.

3. DISCUSSION

From the results in Tables 1 and 2 we can see that a gamma-ray detector with a sensitivity of $\sim 10^{-7}\ \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}$ at $E_\gamma \approx 100$–700 keV may detect (1) fluxes from the decay of a number of r-process nuclei such as ^{125}Sb and ^{194}Os produced in a future Galactic supernova, (2) fluxes from the decay of ^{126}Sn in the Vela supernova remnant, and (3) diffuse fluxes from the decay of ^{126}Sn produced by past supernovae in the Galaxy. Each of these detection possibilities and its significance to our understanding of r-process nucleosynthesis are discussed below.

3.1. *Fluxes from a Future Galactic Supernova*

A future Galactic supernova will announce itself by a powerful neutrino burst even if its optical display is obscured from us. In addition, forward-peaked neutrino-electron scattering events in a water Cerenkov detector such as Super-Kamiokande can provide directional information about the supernova. Even the distance to the supernova can be estimated from the total number and the energies of detected neutrino events since the total energy emitted in neutrinos is known within a factor of a few. The delay between the explosion and onset of gamma-ray transparency leaves time for directing suitable detectors to search for gamma-ray emission from the decay of the r-process nuclei listed in Table 1. Except possibly for ^{144}Ce, these nuclei will have most of their initial abundance produced in the supernova when it becomes transparent. If gamma-ray emission from the decay of the r-process nuclei listed in Table 1 were detected from the supernova, this would prove that these nuclei are produced in supernovae.

In addition, we are interested in determining whether or not these nuclei are produced in relative proportions specified by the solar r-process abundance pattern in supernova r-process events. If every supernova r-process event were to produce the same r-process abundance pattern as that in the solar system, gamma-ray fluxes from the decay of ^{125}Sb, ^{144}Ce, and ^{194}Os produced in a future supernova at a distance of 10 kpc would be detectable for a detector with a sensitivity of $\sim 10^{-7} \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}$ at $E_\gamma \approx 100$–700 keV. Note that although ^{144}Ce may have decayed substantially when the supernova became transparent to gamma rays, the flux at $E_\gamma = 134$ keV from its decay may still be present at the level of $\sim 10^{-7} \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}$. To accurately compare the relative production of these nuclei, one should multiply any detected gamma-ray flux(es) from the decay of each nucleus by the factor $\exp(t/\bar{\tau})$, where t is the time between detection of neutrinos and detection of the gamma-ray flux(es), to account for the decay of the nucleus. If the relative production of these nuclei were indeed specified by the solar r-process abundance pattern, the corrected fluxes would be proportional to $(X^r_\odot/A)(I_\gamma/\bar{\tau})$. The distance to the supernova is not needed for establishing this proportionality; however, a really accurate determination may need a much more sophisticated gamma-ray transport calculation (see, e.g., Woosley, Pinto, & Hartmann 1989) than what we have indicated here.

It is interesting to consider supernova r-process events that produce r-process abundance patterns different from that in the solar system. In fact, distinct supernova sources for the r-process nuclei below and above $A \sim 140$ may be required to explain the meteoritic data on the $^{129}{\rm I}/^{127}{\rm I}$ and $^{182}{\rm Hf}/^{180}{\rm Hf}$ abundance ratios in the early solar system (Wasserburg, Busso, & Gallino 1996). For definiteness, we consider our specific scenario in which the high-frequency supernova source (case H) with $f_{\rm SN}^{\rm H} \sim (30\ {\rm yr})^{-1}$ is mainly responsible for the r-process nuclei near and above $A \sim 195$, while the low-frequency one (case L) with $f_{\rm SN}^{L} \sim (300\ {\rm yr})^{-1}$ is mainly responsible for the r-process nuclei near $A \sim 130$ and the bulk of those between $A \sim 130$ and 195 (Qian, Vogel, & Wasserburg 1998). In this scenario, only gamma-ray fluxes from the decay of ^{194}Os would be detected at the level of $\sim 10^{-7}\ \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}$ from a frequent supernova of case H, and emission from the decay of the lighter nuclei ^{125}Sb, ^{137}Cs, ^{144}Ce, and ^{155}Eu would be unobservable in this case. On the other hand, gamma-ray fluxes from the decay of ^{125}Sb, ^{137}Cs, ^{144}Ce, and ^{155}Eu would all be above $\sim 10^{-7}\ \gamma\ {\rm cm}^{-2}\ {\rm s}^{-1}$ from an infrequent supernova of case L with the expected fluxes ~ 10 times higher than those given in Table 1 where a uniform single r-process source with $f_{\rm SN} = (30\ {\rm yr})^{-1}$ has been assumed to estimate the expected amounts of production δM. Since supernovae of cases H and L should eject the same amount of mass in the r-process nuclei near and above $A \sim 195$ (Qian et al. 1998), gamma-ray fluxes from the decay of ^{194}Os might also be detected at the level given in Table 1 from an infrequent supernova of case L.

We note that our speculative association of black hole remnants with supernovae of case H and neutron star remnants with those of case L can be tested by pulsar searches in addition to observation for gamma-ray emission from the decay of *r*-process nuclei after a future Galactic supernova occurs. If our speculation were correct, only about one out of 10 supernovae would leave behind a neutron star. This would result in many fewer pulsar–supernova remnant associations than usually believed.

3.2. *Fluxes from the Vela Supernova Remnant*

Detection of gamma-ray emission from the decay of ^{126}Sn in the Vela supernova remnant would prove that the *r*-process nuclei near $A \sim 126$ are produced in supernovae. If a gamma-ray detector with a sensitivity of $\sim 10^{-7} \gamma$ cm^{-2} s^{-1} at $E_\gamma \approx 100$–700 keV can be developed, this detection is likely to be the first of its kind to connect *r*-process nucleosynthesis with gamma-ray astronomy since there is no need to wait for a new supernova. If it turns out that gamma-ray emission at $E_\gamma < 100$ keV (i.e., hard X-ray emission) is easier to detect, then the line at $E_\gamma = 87.6$ keV from the decay of ^{126}Sn may merit attention (see Table 2).

We note that the estimates in Table 2 for gamma-ray fluxes from the decay of ^{126}Sn in the Vela supernova remnant are subject to uncertainties in the distance to the Vela pulsar and in the amount of ^{126}Sn produced in the associated supernova. The uncertainty in the distance is basically known since different estimates give $d \approx 125$–500 pc. The uncertainty in the amount of ^{126}Sn produced in an individual supernova is not known. As mentioned in § 3.1, meteoritic data on the ^{129}I/^{127}I and ^{182}Hf/^{180}Hf abundance ratios in the early solar system seem to require distinct supernova sources for the *r*-process nuclei below and above $A \sim 140$ (Wasserburg et al. 1996). In our specific scenario, the *r*-process nuclei near $A \sim 130$ are mainly produced in supernovae of case L, which have a frequency of $f_{\rm SN}^{\rm L} \sim (300 \text{ yr})^{-1}$ and are expected to leave behind neutron star remnants (Qian et al. 1998). In this case, the amount of ^{126}Sn production of δM in equation (3) would be $\sim 5 \times 10^{-6}$ for the supernova of case L associated with the Vela pulsar (see eq. [1]), and the resulting gamma-ray fluxes from the decay of ^{126}Sn would be above $2.2 \times 10^{-7} \gamma$ cm^{-2} s^{-1} at $E_\gamma = 415$, 666, and 695 keV even for the largest distance $d \approx 500$ pc estimated for this pulsar. Therefore, we are hopeful that detection of these fluxes will be accomplished once a gamma-ray detector with the desirable sensitivity of $\sim 10^{-7} \gamma$ cm^{-2} s^{-1} at $E_\gamma \approx 100$–700 keV is developed.

3.3. *Diffuse Fluxes from* ^{126}Sn *Decay and NS-NS Mergers*

Many supernovae occur in the Galaxy during the lifetime of ^{126}Sn. This would result in the diffuse gamma-ray fluxes estimated in Table 2 if supernovae were the main source for the *r*-process nuclei near $A \sim 126$. If NS-NS mergers were the main source for these nuclei, however, there would be no diffuse fluxes from the decay of ^{126}Sn in the Galaxy. This is because with an estimated frequency of $\sim 10^6$ yr^{-1} for Galactic NS-NS mergers (Phinney 1991), the average interval between successive production events is much longer than the lifetime of ^{126}Sn. We suggest that the design of a gamma-ray detector with a point-source sensitivity of $\sim 10^{-7} \gamma$ cm^{-2} s^{-1} take into account the possibility of detecting diffuse fluxes from ^{126}Sn decay so that we may determine whether supernovae or NS-NS mergers are the main source for the *r*-process nuclei near $A \sim 126$. We note that if NS-NS mergers were the main source for these nuclei, point-source fluxes from ^{126}Sn decay would be very high from an event within the last $\sim 10^5$ yr ($F_\gamma \sim 2.9 \times 10^{-6} \gamma$ cm^{-2} s^{-1} at $E_\gamma = 415$, 666, and 695 keV from an event at a distance of ~ 10 kpc).

We consider fluxes from ^{126}Sn decay as a very promising objective for gamma-ray astronomy related to *r*-process nucleosynthesis. Because its lifetime of 1.44×10^5 yr is much longer than the age of the Vela pulsar, gamma-ray fluxes from the decay of ^{126}Sn in the Vela supernova remnant can exist for a very long time into the future, and detection of these fluxes can prove that the *r*-process nuclei near $A \sim 126$ are produced in supernovae. Furthermore, because its lifetime is much longer than the average interval between successive Galactic supernovae but much shorter than that between successive Galactic NS-NS mergers, detection of diffuse gamma-ray fluxes from the decay of ^{126}Sn can eliminate NS-NS mergers as the main source for the *r*-process nuclei near $A \sim 126$. Finally, as in our proposed scenario, if only rare supernovae associated with neutron star remnants were responsible for the *r*-process nuclei near $A \sim 130$, then gamma-ray fluxes from the decay of ^{126}Sn in the Vela supernova remnant would be much easier to detect.

4. CONCLUSION

We have discussed detection possibilities for gamma-ray emission from the decay of *r*-process nuclei produced in supernovae and their significance for our understanding of *r*-process nucleosynthesis. In particular, we have found that a gamma-ray detector with a sensitivity of $\sim 10^{-7} \gamma$ cm^{-2} s^{-1} at $E_\gamma \approx 100$–700 keV may detect the emission from the decay of ^{125}Sb, ^{137}Cs, ^{144}Ce, ^{155}Eu, and ^{194}Os produced in a future Galactic supernova. In addition, such an instrument may detect the emission from the decay of ^{126}Sn in the Vela supernova remnant and the diffuse emission from the decay of ^{126}Sn produced by past supernovae in our Galaxy. The required detector sensitivity is similar to what is projected for the proposed detector ATHENA. Both the detection of gamma-ray emission from the decay of several *r*-process nuclei (e.g., ^{125}Sb and ^{194}Os) produced in future Galactic supernovae and the detection of emission from the decay of ^{126}Sn in the Vela supernova remnant would prove that supernovae are a site of the *r*-process. Furthermore, the former detection would allow us to determine whether or not the *r*-process nuclei are produced in relative proportions specified by the solar *r*-process abundance pattern in supernova *r*-process events. Finally, detection of diffuse gamma-ray emission from the decay of ^{126}Sn in our Galaxy would eliminate NS-NS mergers as the main source for the *r*-process nuclei near $A \sim 126$. In view of these returns, we strongly urge that a gamma-ray detector with a sensitivity of $\sim 10^{-7} \gamma$ cm^{-2} s^{-1} at $E_\gamma \approx 100$–700 keV be developed in the near future.

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