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The de-excited energy of electron capture in accreting neutron star crusts

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Abstract When a daughter nucleus produced by electron capture takes part in a level transition from an excited state to its ground state in accreting neutron star crusts, thermal energy will be released and heat the crust, increasing crust temperature and changing subsequent carbon ignition conditions. Previous studies show that the theoretical carbon ignition depth is deeper than the value inferred from observations because the thermal energy is not sufficient. In this paper, we present the de-excited energy from electron capture of rp-process ash before carbon ignition, especially for the initial evolution stage of rp-process ash, by using a level-to-level transition method. We find the theoretical column density of carbon ignition in the resulting superbursts and compare it with observations. The calculation of the electron capture process is based on a more reliable level-to-level transition, adopting new data from experiments or theoretical models (e.g., large-scale shell model and proton-neutron quasi-particle random phase approximation). The new carbon ignition depth is estimated by fitting from previous results of a nuclear reaction network. Our results show the average de-excited energy from electron capture before carbon ignition is $\sim$0.026 MeV/u, which is significantly larger than the previous results. This energy is beneficial for enhancing the crust's temperature and decreasing the carbon ignition depth of superbursts.

Key words: stars: neutrons — nuclear reactions — nucleosynthesis — abundances

1 INTRODUCTION

Accreting neutron stars in binaries are regarded as the explanation of many high energy astronomical phenomena, such as Type I X-ray bursts (Belian et al. 1976), intermediate duration bursts (Cornelisse et al. 2000) and superbursts (Cornelisse et al. 2000). These phenomena have been studied extensively. For example, Peng & Ott (2010) recalculated the helium ignition conditions on the crust of accreting neutron stars by using improved nuclear reaction rates. Cavecchi et al. (2013) studied flame propagation on their surfaces during Type I X-ray bursts. Parikh et al. (2013) presented a detailed review of nucleosynthesis that occurs in accreting neutron stars.

Astronomical observations indicate that the heat source of a superburst is about three orders of magnitude higher than that of normal Type I X-ray bursts and the associated timescale is several hours compared to a few tens of seconds for normal Type I X-ray bursts (Chamel & Haensel 2008; Keek et al. 2014). Previous research shows the main radiation is thermal radiation and it is larger than the energy from accretion, neutrino cooling, rotation and so on. Type I X-ray bursts are thought to be powered by the rapid proton-capture process (rp-process) (Schatz 2006), while superbursts are caused by the unstable burning of carbon at density $10^8 - 10^9$ g cm^{-3}(Gupta et al. 2007; Parikh et al. 2013). The ignition conditions of carbon burning such as temperature are crucial to explain the associated observational phenomena. Gupta et al. (2007) proposed that de-excited energy (the released energy as a nucleon transits from an excited state to its ground state) of electron capture (EC) is an important heat source in crusts of accreting neutron stars and helps to explain superbursts, but the energy is not sufficient. After that, Cooper & Kaplan (2010) investigated the case of isolated magnetars. They concluded that de-excitation of EC is a quite efficient way for thermal energy to be released in neutron star/magnetar crusts.

Previous calculations of EC were performed under the approximation of zero temperature, and did not consider a detailed level-to-level transition of specific nuclei involved in the process. Haensel & Zdunik (1990) used 1/4 times the difference between electron Fermi energy and threshold as the de-excited energy when the electron Fermi energy is approaching the threshold. Gupta et al. (2007) only considered allowed Gamow-Teller (GT) transitions in their calculation. In fact, the large-scale shell model (LSSM), which includes forbidden transitions, shows that the GT levels are generally much higher than previous estimations (see e.g., the review of Langanke & Martínez-Pinedo 2003), with induces a significant decrease in EC rates (in general, by one order of magnitude or more for intermediate nuclei). Hence the de-excited energy by EC should significantly change as updated data are adopted. Moreover, the validity of the EC heat mechanism strongly depends on details of the transition process and the associated reaction rates. In this paper, we make a quantitative calculation of this problem in the case of a non-zero temperature, especially for the initial stage after the birth of rp-process ash. We adopt a detailed electron capture process based on a level-to-level nuclear shell model, including the most updated and accurate level data (such as charge-exchange reaction experiments, LSSM and proton-neutron quasi-particle random phase approximation (pn-QRPA)). It is a more feasible method to obtain reliable de-excited energy in the accreting neutron star crusts and in other similar environments in the future.

The paper is organized as follows. In Section 2, we present our method, including initial input physics, and the calculation method used for EC and de-excited energy. In Section 3, we present our calculation results and analysis. Some discussions and a conclusion are presented in Sections 4 and 5, respectively.

2 METHOD

2.1 Initial Composition in the Accreting Neutron Star Crusts as the EC Occurs

It is believed that the accreted matter (mainly H and He) from the companion experiences explosive H/He burning in the crust of neutron stars. Early studies (e.g., Wallace & Woosley 1981) showed the final production of the explosive burning during the burst (10–100 s) of an H-rich mixture was Fe group nuclei via the rp-process (Wallace & Woosley 1981). ^{56}Ni was considered to be the most abundant final product. Detailed calculations using a shell-flash model with constant pressure showed the final product should be beyond Fe. Using a sufficient reaction network, Schatz et al. (2001) found the rp-process resulted in the synthesis of nuclei far beyond Fe and terminated at A$\sim$100 when accretion rates of neutron stars reached the Eddington accretion rate or higher. Using both shell-flash and realistic models of accreting neutron stars with the full nuclear reaction network up to Bi, Koike et al. (2004) found that ^{64}Zn was the most abundant element after the burst. Haensel et al. (1990, 2003) used a single representative nucleus, ^{56}Fe or ^{106}Pb, to investigate heat in the crust (Haensel & Zdunik 2003, 1990). In this paper we adopt rp-process ashes as the initial composition for EC (Koike et al. 2004). Of course, the products of the rp-process may be quite different due to the different accretion rates, ignition pressure of nuclear burning and so on. Here, we choose Model 1 in Koike et al. (2004) as an example to show our method. In this composition, Zn is the most abundant nucleus (34.7% by mass abundance). The mass abundance of the other main nuclei, ^{56}Ni, ^{64}Ga,

^{60}Ni, ^{55}Co, ^{32}S and ^{39}K, are 18.5%, 8.23%, 6.39%, 3.44%, 3.43% and 3.18%, respectively. There are also some residual amounts of ^{12}C (3.65% by mass) and ^{4}He (2.24% by mass). Here we do not include all the nuclei that show low abundance because they have little influence on the final results. According to the definition of electron fraction, we calculate the electron fraction $Y_{\rm e} = 0.48$ for the initial composition.

2.2 Initial Density and Temperature as the EC Occurs

A typical neutron star model with mass $M = 1.4\ M_\odot$ and radius $R = 10$ km is used in this paper. Previous research showed that, to avoid severe neutrino losses, the heat source powering the thermal emission of the neutron star must be located at or near the outer crust, i.e., within the neutron star's outermost 100 m (Kaminker et al. 2009, 2006; Altamirano et al. 2012) (recent research indicated the actual value might be deeper (Schatz et al. 2014) or shallower (Degenaar et al. 2013)). In fact, the location which is shallower or deeper (i.e., the density is lower or higher) is not important for our results; we will discuss this later. As an example, we set the location where the EC reaction occurs at a crust depth of $\sim 10^4$ cm.

The previous calculation indicated a reasonable He ignition column density is $\sim 10^{11}$ g cm^{-2} for superbursts and has been proposed as a possible explanation for a superburst from 4U 0614+091 (Peng & Ott 2010; Kuulkers et al. 2010). One should note that this value is significantly larger than the case of pure He. For example, the ignition column density of He is 2×10^8 g cm^{-2} for a fixed pressure of $\sim 4{\times}10^{22}$ erg cm^{-3} (Strohmayer & Bildsten 2006). The detailed ignition column density is also related to accretion rate and composition (Schatz et al. 1999). Since He burning is the subsequent reaction after H burning (especially for the rp-process here), and the temperature of the rp-process is very high (the peak temperature of the rp-process may be larger than 10^9 K, Schatz 2006), the interval between the completion of the rp-process and the ignition of He is quite small. We assume the rp-process ashes appear approximately at the location of column density $\sim 10^{11}$ g cm^{-2}, i.e., the average density in the outer crust is 10^7 g cm^{-3}.

Now we calculate the density at the location where crust depth is 10^4 cm by using the hydrostatic equilibrium equation, assuming that both the electron degeneracy pressure and the magnetic pressure counterbalance gravity. Because the temperature range of soft X-ray radiation is on the order of 10^8 K, the radiation pressure is so little that it could be reasonably ignored. The spin of the neutron star also has little influence on the hydrostatic equilibrium since the gravitational acceleration is much larger than the centrifugal acceleration. Therefore, the equation of hydrostatic equilibrium is

$$g\bar{\rho}\Delta R = P_{\rm e,i} - P_{\rm e,o} + \frac{1}{8\pi}(B_i^2 - B_o^2)\,. \tag{1}$$

The left side of Equation (1) represents gravity, in which the gravitational acceleration $g = G\frac{M}{r^2}$, where G is the gravitational constant, r is the distance from the center of the neutron star to the crust, and M is approximately equal to the mass of the neutron star. $\bar{\rho} = 10^7$ g cm^{-3} and $\Delta R = 10^4$ cm are the average density and thickness of the crust, respectively. The first and second terms on the right of Equation (1), $P_{\rm e,i}$ and $P_{\rm e,o}$, are electron degeneracy pressure of the inner and outer boundary, respectively. We assume that motions of electrons are extremely relativistic, so the electron degeneracy pressure can be written as (Shapiro & Teukolsky 1983),

$$P_{\rm e} = \hbar c(3\pi^2)^{1/3}\frac{(n_{\rm e})^{4/3}}{4}\,, \tag{2}$$

where $\hbar$ is the Plank constant, c is the speed of light and $n_{\rm e} = \rho Ye N_{\rm A}$ is electron number density, in which $N_{\rm A}$ is Avogadro's constant. The electron degeneracy pressure at the magnetar surface is zero ($P_{\rm e,o} = 0$). At the inner boundary, $P_{\rm e,i}$ is determined by the local density ρ_i. The last term of Equation (1) denotes the magnetic pressure difference between the inner boundary and the outer one of the shell, where B_i and B_o are magnetic field strength for the inner and outer boundaries respectively. Both theoretical research and astronomical observations show that the typical magnetic field strength of a neutron star is $\sim 10^{12}$ G, so we set B_i equal to 10^{12} G and the magnetic field distribution satisfies the relationship $B(r) = B_i(\frac{R_B}{r})^3$ (Thompson 2003), where $R_B = 9.9$ km. In all, we now rewrite Equation (1) as follows

$$g\bar{\rho}\Delta R = \hbar c(3\pi^2)^{1/3}\frac{\left(\rho_i Y_{\rm e} N_A\right)^{4/3}}{4} + \frac{B_i^2}{8\pi}\left[1 - \left(\frac{9.9}{10}\right)^6\right]. \tag{3}$$

The solution for Equation (3) is ρ_i=8.95×10^7 g cm^{-3}, i.e., the initial density of matter composing the rp-process ashes is 8.95×10^7 g cm^{-3}. If the location is shallower than 10^4 cm, the density will be much lower than ρ_i. We will discuss this situation in Subsection 4.2.

The initial temperature of EC is set to 4.2×10^8 K which is the same as what was used by Gupta et al. (2007). Although the maximum temperature after EC may reach 5.7×10^8 K according to the calculation of Gupta et al. (2007), such variation in temperature slightly influences the EC. So, we assume the temperature to be constant for the sake of simplicity. Now all basic parameters describing the physical environment for EC, including temperature, initial density, initial electron fraction and initial composition, are determined.

2.3 Calculation Method of EC Rates

In this paper, we use the shell model to quantitatively calculate EC rates. The precise EC rate must account for all transitions from all initial states i to different final states j. For a nucleus with charge number Z and mass number A in equilibrium at temperature T, each initial state i of the parent nucleus will produce a final transition intensity distribution under the action of the Fermi operator and GT transition operator as the EC occurs. The EC rate λ can be written as (Pruet & Fuller 2003)

$$\lambda = \ln 2 \sum_i \frac{(2J_i + 1)\, e^{-E_i/(k_B T)}}{G(Z, A, T)} \sum_j \left(\frac{|M_{GT}|^2_{ij}}{10^{3.59}} + \frac{|M_F|^2_{ij}}{10^{3.79}}\right)\phi_{ij}(\rho, T, Y_{\rm e}, Q_{ij})\,, \tag{4}$$

where J_i and E_i are the spin and excited energy of the parent states respectively, k_B is the Boltzmann constant, $G(Z, A, T)$ is the nuclear partition function, and $|M_{GT}|^2_{ij}$ and $|M_F|^2_{ij}$ are the GT and Fermi matrix element for the transition respectively, denoting the reduced transition probability from one of the initial states to possible final states. The phase space integral ϕ_{ij} is defined as

$$\phi_{ij}(\rho, T, Y_{\rm e}, Q_{ij}) = \int_\ell^\infty w^2(Q_{ij} + w)^2 G(Z, w) f_{\rm e} dw\,, \tag{5}$$

where w is the total rest mass and kinetic energy of the electron (all energies are in units of $m_{\rm e}c^2$, where $m_{\rm e}$ is the mass of an electron), and $G(Z, w)$ is the the Coulomb wave correction factor. $Q_{ij} = (m_p - m_d)c^2 + E_i - E_j$, where m_p and m_d are the mass of the parent and daughter nucleus respectively, and E_j is the excited energy of the daughter state. The EC threshold is ℓ =1 for $Q_{ij} \geq -1$ and $\ell = |Q_{ij}|$ for $Q_{ij} < -1$. $f_{\rm e} = \{1 + \exp\left[(w - \mu_{\rm e})/k_B T\right]\}^{-1}$ is the electron Fermi-Dirac distribution function, where $\mu_{\rm e}$ is the electron chemical potential.

Theoretically, the EC rates can be calculated by Equation (4) running over all levels. However, it is unlikely to attain an accurate distribution for all excited states of each nucleus at present in both experiments and theories, especially for the high excited states whose distribution is almost continuous (particularly for heavy nuclei). As the parent nucleus is in the ground state, the distribution of nuclear spins and excitation levels for the daughter nuclei can be found in the present experimental data (NNDC 2013) or estimated by using the nuclear shell model. As the parent nucleus is in low

Table 1 ^{64}Zn Energy Levels from Experiment (NNDC 2013^a)

E_{level} (keV)	J^π
0.0	0^+
991.56	2^+
1799.36	2^+
1910.32	0^+
2306.75	4^+
2609.46	0^+
2736.53	4^+
...	...

Notes: ^{a} National Nuclear Data Center (*http://www.nndc.bnl.gov*).

excited states, theoretical estimation is effective, such as the LSSM (see e.g., Langanke & Martínez-Pinedo 1999, 2000) and the QRPA (Nabi et al. 2008; Nabi & Sajjad 2008). As the parent nucleus is in high excited states, e.g., $E_i > 3$ MeV in LSSM, a special hypothesis is essential, in which the transitions from the excitation energy of any initial state E_i of the parent nucleus to all the possible final states, the GT distribution moves upward in the daughter nucleus by the same amount as the energy separation between the ith parent state and the parent ground state. That means the GT transition operator results in a similar intensity distribution as the transition from the ground state, and only the location of the level is changed. This is the so-called "Brink hypothesis" (Aufderheide et al. 1994). The LSSM calculations demonstrated the "Brink hypothesis" is valid for the bulk of GT strengths (Langanke & Martínez-Pinedo 1999). Since the temperature which is considered in this paper is not sufficiently high (several times 10^8 K), most of the parent nuclei are in the ground state. For example, the spin of ^{64}Zn in ground state is zero, so $(2J_0+1)e^{-E_0/k_BT} = 1$, while the first excited energy of ^{64}Zn, E_1, is 0.991 MeV and its spin J_1 is 2 (see Table 1), so $(2J_1+1)e^{-E_1/k_BT} = 4.51 \times 10^{-50}$. This means the probability of ^{64}Zn occupying the first excited state is almost zero. Therefore the "Brink hypothesis" will not bring any substantial deviation. We adopt all relevant data whenever experimental or theoretical estimations are available.

2.4 The Calculation of the EC De-excited Energy

Considering the transition possibility to each final state and the energy difference between the excited state and the ground state of the daughter nucleus, the average de-excited energy $\bar{E_x}$ for a nucleus after one EC is written as

$$\bar{E_x} = \sum_i \sum_j \frac{\ln 2(2J_i+1)e^{-E_i/(k_BT)}(|M_{GT}|^2_{ij}/10^{3.59} + |M_F|^2_{ij}/10^{3.79})\phi_{ij}(\rho, T, Y_{\mathrm{e}}, Q_{ij})}{G(Z,A,T)\lambda}\Delta E_{ij}, \tag{6}$$

where ΔE_{ij} is the de-excited energy from the excited state E_j to the ground state of daughter nuclei. When the parent nuclei are in ground states, the excitation levels for the daughter nuclei can be found in the references in the footnote of Table 2. When the parent nuclei are in excited states, the excitation levels are handled as described in Subsection 2.3.

In the pioneering work of Haensel & Zdunik (1990), they have pointed out an interesting phenomenon in the EC. If the parent nucleus is an even-even nucleus (both Z and A are even), it will become an odd-odd nucleus after EC by changing one of the protons into a neutron. The EC threshold of the newly born odd-odd nucleus is generally lower than that of the previous even-even nucleus, so a secondary EC will occur immediately. Similar continuous ECs may occur several times for isobaric nuclei. For comparison, we define the integrated energy released by per amu, E_u, as

$$E_u = \sum_k \frac{\chi_k}{A_k} \sum_n \bar{E}_x(k,n)\,, \tag{7}$$

Table 2 List of Nuclei ($T = 4.2\times10^8$ K, $\rho = 8.95\times10^7$ g cm^{-3}, $Y_\mathrm{e} = 0.48$)

^AZ (1)	$Q_{\mathrm{thr,gs-gs}}$ (MeV) (2)	λ (s^{-1}) (3)	$\bar{E}_x$ (MeV) (4)	τ (s) (5)
^{64}Ga$^{(a)}$	–6.65	1.32E−01	3.42E+00	5.27E+00
^{64}Zn$^{(b)}$	1.09	7.94E−04	5.86E−02	8.73E+02
^{64}Cu$^{(c)}$	–1.16	6.91E−03	5.14E−05	1.00E+02
^{60}Ni$^{(d)}$	3.33	6.94E−24	3.33E−12	9.99E+22
^{60}Co$^{(e)}$	0.75	4.23E−08	3.27E−12	1.64E+07
^{56}Ni$^{(f)}$	–1.62	6.94E−03	1.72E+00	9.99E+01
^{56}Co$^{(g)}$	–4.06	1.17E−03	4.20E+00	5.93E+02
^{56}Fe$^{(h)}$	4.21	4.72E−34	4.28E−03	1.47E+33
^{55}Co$^{(i)}$	–2.94	1.09E−02	2.99E+00	6.33E+01
^{55}Fe$^{(j)}$	0.28	2.29E−04	2.46E−02	3.02E+03
^{55}Mn$^{(k)}$	3.11	1.76E−22	4.23E−02	3.93E+21

Notes: (1) List of 11 nuclei that take part in the EC reaction at the initial stage of He ignition, sorted in order of mass number. The second column lists the the EC threshold of the nuclei. The third column lists the EC rates. The fourth column lists the average de-excited energies. The last column lists the half-life of the nuclei. (2) (a) NNDC (2013); (b) Hitt et al. (2009); (c) NNDC (2013); (d) Sarriguren et al. (2003); (e) Langanke & Martínez-Pinedo (1999); (f) Nabi et al. (2008); NNDC (2013); (g) Langanke & Martínez-Pinedo (1999); Nabi et al. (2007); (h) Dzhioev et al. (2010); (i) Nabi et al. (2007); (j) Nabi (2011); NNDC (2013); (k) NNDC (2013); Sarriguren et al. (2003).

where χ_k and A_k are the mass abundance and mass number of the kth nucleus respectively, and n denotes the nth EC for a nucleus. $\bar{E}_x$ depends on the type of nucleus and corresponding environment.

3 RESULTS

In this section, we examine how much thermal energy will be released by EC during the initial stage of the rp-process ashes. With the initial conditions in Section 2, the temperature $T = 4.2 \times 10^8$ K, the density $\rho = 8.95 \times 10^7$ g cm^{-3} and electron fraction $Y_\mathrm{e} = 0.48$, then the electron chemical potential $\mu_\mathrm{e} = 1.87$ MeV (including the rest mass).

We define the EC threshold from ground state to ground state transition, $Q_{\mathrm{thr,gs-gs}}$, as $(m_d - m_p)c^2$. In this definition, a negative threshold denotes that the EC reaction does not require extra electronic energy; a positive threshold denotes that only the electrons whose energy exceeds the corresponding threshold can effectively take part in the EC reaction. That is, if electron chemical potential is lower than the threshold, only a small number of electrons in the high-energy tail can take part in the reaction. Consequently, their rates are very small. Table 3 shows the EC threshold, EC rates, average de-excited energy and half-life τ ($\tau = \ln 2/\lambda$) of the nuclei.

To ensure our calculation results are reliable, we have compared them with those in the previous references such as Langanke & Martínez-Pinedo (2001). In Table 2, one can find the electron capture rates, average released energy per nuclei and half-life are quite different for these nuclei due to their different thresholds. For the most abundant nuclei ^{64}Zn, the electron chemical potential is larger than its threshold at this time, and the EC can proceed effectively. However, this reaction is dominated by the ground state to ground state transition, so that the $\bar{E}_x$ is small. Although the electron chemical potential is larger than the threshold of ^{60}Co, we find the released energy is so little that it can be ignored. This is because the energy originates from de-excitation of the daughter nucleus. The first excitation level of the daughter nucleus, ^{60}Fe, is ∼2.1 MeV, but the electron chemical potential is 1.12 MeV larger than the threshold, so the transition probability to the first excited state of ^{60}Fe is small. Therefore, in summary, the released energy strongly depends on the distribution of levels in the daughter nuclei, in addition to the reaction rate. This rule is also suitable for the case when μ_e is less than $Q_{\mathrm{thr,gs-gs}}$. For example, the electron chemical potential is less than the threshold

Table 3 The EC Reaction Chains of the Main Nuclei

^{A}Z	EC reaction chains
^{64}Zn	^{64}Zn(e$^-$, ν_e)^{64}Cu(e$^-$,ν_e)^{64}Ni
^{56}Ni	^{56}Ni(e$^-$, ν_e)^{56}Co(e$^-$, ν_e)^{56}Fe
^{64}Ga	^{64}Ga(e$^-$, ν_e)^{64}Zn(e$^-$, ν_e)^{64}Cu(e$^-$, ν_e)^{64}Ni
^{60}Ni	^{60}Ni(e$^-$, ν_e)^{60}Co(e$^-$, ν_e)^{60}Fe
^{55}Co	^{55}Co(e$^-$, ν_e)^{55}Fe(e$^-$, ν_e)^{55}Mn(e$^-$, ν_e)^{55}Cr

of ^{56}Fe. Although the capture rate of ^{56}Fe is almost equal to zero, its average de-excited energy is 4.28×10^{-3} MeV per capture. For the case of ^{60}Ni, since the transition is dominated by the ground state to ground state case, both its capture rate and average released energy are almost equal to zero.

Another important output is the half-life of the parent nuclei. For example, the half-life of ^{64}Zn is 873 s $\sim$13 minutes, but the observed recurrence times of the superburst are on the order of one year, so most ^{64}Zn will be quickly depleted, changing to ^{64}Cu. Because the electron chemical potential is much higher than the EC threshold of ^{64}Cu ($Q_{\rm thr,gs-gs} = -1.16$ MeV), ^{64}Cu will continue to quickly capture electrons (this is the "even-even nucleus effect"), producing more stable ^{64}Ni. Fortunately, the threshold of ^{64}Ni (7.82 MeV) is much higher than the electron chemical potential, so ^{64}Ni is stable in this environment. In a similar analysis of the other nuclei, we find that ^{56}Ni, ^{64}Ga, ^{60}Ni and ^{55}Co will be quickly depleted, producing ^{56}Co, ^{64}Zn, ^{60}Co and ^{55}Fe, respectively. Continuing EC occurs and generates ^{56}Fe, ^{64}Ni, ^{60}Fe and ^{55}Cr, respectively (their reaction chains are shown in Table 3). Furthermore, for nuclei with high thresholds such as ^{12}C ($Q_{\rm thr,gs-gs} = 13.88$ MeV), they can avoid EC for a long time. Thus in summary, the main stable nuclei are ^{56}Fe, ^{64}Ni, ^{60}Fe, ^{55}Cr, ^{12}C and ^{4}He. At the same time, the electron fraction $Y_{\rm e}$ will decrease to $\sim$0.46 after the initial EC stage.

By using Equation (7), we get $E_u = 26.26$ keV/u, in which the contribution from ^{64}Zn, ^{56}Ni, ^{64}Ga and ^{55}Co are 0.32, 19.56, 4.47 and 1.91 keV/u, respectively. The accretion rates of the neutron star are $10^{16} - 10^{18}$ g s^{-1} (Schatz et al. 2014). To estimate an extreme situation, we assume all the accreted matter will experience the EC stage described above (of course, in fact, only partially accreted matter experiences rp-process burning (Schatz et al. 1999)). The maximal limit of released thermal energy is $2.53 \times 10^{32} - 10^{34}$ erg s^{-1} corresponding to different accretion rates. The superburst releases $\sim$10^{42} erg per burst (Parikh et al. 2013). Although the de-excited energy we calculated cannot supply the amount of energy needed for a superburst, it still plays an important role as the ratio of the rp-process ashes to the accreted matter is high.

After the initial EC stage, the matter will be compressed due to the accumulation of accreted matter on the surface and gravitation. The density will increase with time till the carbon ignition in the heavy-element bath ($10^8 - 10^9$ g cm^{-3}). Gupta et al. (2007) tracked the evolution of the matter and the energy released by EC up to electron chemical potential $\sim$20 MeV using a large nuclear reaction network. Here we do not consider the subsequent EC reactions, and an estimation of the influence of our results on the final carbon ignition condition will be discussed in the following section. Our method introduced above is valid in the nuclear reaction network.

4 DISCUSSION

4.1 An Estimation of the Column Density Required for Carbon Ignition

The previous study by Gupta et al. (2007) demonstrated that most of the de-excited energy from the EC is deposited in the crust, rather than being carried away by neutrinos. This leads to a hotter crust and decreases superburst ignition depths and recurrence times. In their work, they set de-excited energy at $\mu_{\rm e} = 1$ MeV to zero. Our results show the integrated de-excited energy at $\mu_{\rm e} = 1.87$ MeV is 26 keV/u. In Gupta et al.'s work, however, this value is ~ 2 keV/u without consideration of the de-excited energy at the initial stage. Therefore, the improved integrated de-excited energy based on our results will be much larger than the previous case if the same nuclear reaction network is adopted to describe the subsequent evolution. The observation inferred that a reasonable column density for carbon ignition is $5 \times 10^{11} - 2.7 \times 10^{12}$ g cm^{-2} (Cumming et al. 2006). The average column density for carbon ignition is $\sim 1.6{\times}10^{12}$ g cm^{-2} and the corresponding average electron chemical potential is ∼3.5 MeV arising from equations describing the thermal structure of the crust. The fiducial integrated de-excited energy at $\mu_{\rm e} = 3.5$ MeV is $\sim$ 10 keV/u (see Gupta et al. 2007, fig. 4). The released energy after the initial stage is very small, but even so the new integrated de-excited energy at carbon ignition is at least 2.6 times larger than the previous case.

The column density of carbon ignition $y_{\rm C_{ign}}$ is roughly linear with carbon ignition temperature (see Gupta et al. 2007, black dots in fig. 9). The reason is that unstable C ignition must meet a condition: the nuclear burning timescale is less than the gravitational collapse timescale. The burning timescale is inversely proportional to nuclear reaction rate, which is proportional to the square of number density. The number density of C in the crust increases with column density. This causes the increase of nuclear reaction rate at a lower ignition temperature, triggering the unstable C ignition. On the other hand, the increase of column density will increase energy loss due to the plasma neutrino emission process. This causes the temperature to not be too high. We fit the relationship between T and $y_{\rm C_{ign}}$ by

$$\lg y_{\rm C_{ign}} = 15.45407 - 5.95786\, T_9\,, \tag{8}$$

where T_9 is the temperature in units of 10^9 K (GK). Previous calculations show that $y_{\rm C_{ign}}$ is $3.7{\times}10^{12}$ g cm^{-2} as the accretion rate is 0.3 times the Eddington mass accretion rate, and the corresponding ignition temperature is ∼0.485 GK. This means that the de-excited energy, 10 keV/u, can enhance the ignition temperature by ∼0.065 GK. Assuming the change in specific heat is slight in this process, the improved temperature based on our calculation can be expected to be ∼0.59 GK. Using Equation (8), we get the new ignition column density $y_{\rm C_{ign}} = 8.69 \times 10^{11}$ g cm^{-2}, which is in accordance with observations (e.g., Altamirano et al. 2012). If the Cooper-pairing neutrino emissivity is suppressed, the ignition column density can be lower.

4.2 The Influence of Initial Density and Composition

In this paper, the initial density is set to 8.95×10^7 g cm^{-3}. In Gupta et al.'s work, however, the initial density is set to 6.2×10^6 g cm^{-3}. We also calculated the de-excited energy at the same density, and found the integrated de-excited energy $E_u = 23.8$ keV/u, which is just a little smaller than the current value. Therefore our results are not sensitive to the initial density. This is because the released energy is dominated by nuclei whose EC threshold is negative (they do not need additional energy from the electrons). Even if density approaches zero at the neutron star's surface, EC of those rp-process ashes will also occur and they release thermal energy according to our calculation. This energy was not included in the previous works.

Our results are closely dependant on the composition of the rp-process ash. The product of the rp-process can vary a lot due to different physical inputs (Koike et al. 2004). Only the composition of Model 1 in Koike et al. (2004) is used in this paper. We analyzed Models 2 and 3 in Koike et al. (2004), and found the dominant nuclei for de-excited energy such as ^{68}Ge, ^{72}Se, ^{76}Kr and ^{81}Sr also have very small, even negative, thresholds. The initial electron chemical potential is about 1 MeV, so a large amount of de-excited energy will be released. Therefore our conclusion is valid for the different composition of rp-process ashes.

4.3 The Influence of the Magnetic Field

It is known that there is a strong magnetic field both at the surface and inner part of the neutron star. Strictly speaking, the magnetic field will influence the EC rate. However, only when the magnetic field is stronger than the critical magnetic field, 4.414×10^{13} G, can it substantially affect the weak interaction rates (including EC, β decay and so on) (Luo & Peng 1997; Zhang et al. 2006, 2010). Recent statistical results show the magnetic field of the majority of neutron stars is in the range $10^{11} - 10^{13}$ G, including both old and young neutron stars (Igoshev & Kholtygin 2011). Especially for an accreting neutron star that undergoes a superburst, their magnetic fields are often even lower than the normal ones. So, the magnetic field has a negligible influence on the rates and de-excited energy in this environment.

5 CONCLUSIONS

We have studied the de-excited energies of EC in accreting neutron star crusts by using rp-process ash. These energies can be locally stored in the neutron star's crust and will affect the unstable conditions required for carbon ignition. In particular, we have estimated the temperature and column density required for carbon ignition. We conclude that the external energy of EC at the initial EC stage will significantly enhance the temperature and decrease the column density required for carbon ignition, and can explain some observational phenomena related to superbursts. The efficiency of our results strongly depends on the type of composition, and it is valid for regular rp-process ashes. In addition, the calculation method of the de-excited energy via EC is also valid in some other astronomical phenomena such as the thermal source for Type I X-ray emission from accreting neutron stars.

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