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Influence of Magnetic Field Decay on Electron Capture in Magnetars

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Abstract. The de-excited energy of electron capture (EC) induced by magnetic field decay may be a new source for heating magnetar crust, so we do a quantitative calculation on EC process near the outer crust and analyse their influence on persistent X-ray radiation of magnetars, adopting the experimental data or the results of theoretical model (including the large-scale shell model and quasi-particle random phase approximation).

Key words. Electron capture: magnetar: X-ray emission.

1. Introduction and method

Magnetars, neutron stars with ultrastrong magnetic field, have been addressed by many researchers. In recent years, the observations of magnetars suggest that the luminosity of persistent X-ray radiated from magnetars is likely the radiation of thermal origin (Ibrahim *et al.* 2004; den Hartog *et al.* 2008; Camilo *et al.* 2007; Thompson *et al.* 2002; Götz *et al.* 2006). However, the considerable mechanism of X-ray source is not clear till now. Cooper & Kaplan (2010) proposed a new heating mechanism in magnetar crusts. They argued that the magnetic pressure is comparable to electron degeneracy pressure in the magnetar crust, and magnetic pressure partially supports the crust against gravity. When the magnetic pressure decreases and the crust shrinks, the density and electron Fermi energy in crusts increase, which then induces exothermic electron capture (EC) of nuclide (i.e., magnetic field decay-induced EC). In fact, the validity of this heating mechanism strongly depends on EC rate and the heat released during EC process.

Here we introduce our quantitative results on this problem. We employ a magnetar model with a typical mass $M = 1.4M_{\odot}$ and radius $R = 10$ km (Thompson 2003). The previous researches showed that, to avoid severe neutrino losses, the heat source powering the thermal emission of the magnetar must be located at or near the outer crust, i.e., within the magnetar's outermost 100 m. Hence, we assume the outer crust's thickness to be 0.1 km, which is much less than its radius. We assume that the composition of the crust is the final product of the rp-process (Koike *et al.* 2004). Of course, the product of the rp-process may be quite different due to the different accretion rate, ignition pressure of nuclear burning and so on. We choose here model 1a as an example, in which ^{64}Zn is the most abundant nuclide whose mass fraction is

34.7%. Then it is easy to obtain the electron fraction $Y_e \sim 0.48$ according to the definition of electron fraction. We then estimate the average density $\bar{\rho}$ of the crust by using the hydrostatic equilibrium condition.

In our work, shell model is adopted to calculate EC rates. Strictly speaking, precise rate must consider all transitions from the different initial states to the different final states (Langanke & Martinez-Pinedo 2000; Pruet & Fuller 2003). However, it is unlikely to make an accurate distribution for all the excited states of each nucleus because the distribution of the highly excited states is almost continuous (particularly for heavier nuclei). For the case of the ground state of parent nuclei, the nucleus spin and excited level distribution of daughter nuclei can be found in the existing experimental data or estimated by using the nuclear shell model. For the excited states of parent nuclei, we adopted the results of large-scale shell-model (LSSM, see Langanke & Martinez-Pinedo 1999, 2000), proton–neutron quasi-particle random phase approximation (pn-QRPA) theory (see e.g., Nabi & Saijad 2008) or the 'brink hypothesis'. LSSM's calculations indicate that 'brink hypothesis' is valid for the bulk of GT strength (Langanke & Martinez-Pinedo 1999). Since the surface temperature of magnetars are not high enough (10^7–10^8 K), most of the parent nuclei are in the ground state. Therefore, 'brink hypothesis' will not bring any substantial deviation. We adopted all the level data whenever charge–exchange experiment is available (NNDC 2012).

2. Results

In the initial stage of our model, the electron chemical potential in the crust is 3.68 MeV. EC threshold energy of the ground state to ground state transition is defined as the mass of daughter nucleus minus that of mother nucleus. So the negative threshold energy indicates that EC reaction does not require additional electronic energy; the positive threshold energy indicates that only the electrons whose energy exceeds the corresponding threshold energies have EC reaction effectively, that is, if electron chemical potential is lower than the threshold energies, only a small number of electrons in high-energy tail can take part in the reaction. Certainly, their rates are very low. We find, for most of the nuclei, EC rate is dominant by the low energy transition. For the most abundant nuclide, ^{64}Zn, weighed mean of de-excited energy $\bar{Q}$ (^{64}Zn) $= 0.42$ MeV. Since the life of magnetic field is much larger than that of ^{64}Zn, most of ^{64}Zn will quickly decay into ^{64}Cu. Because the electron chemical potential is much higher than the EC threshold energy of ^{64}Cu, ^{64}Cu will continue to capture electrons quickly and produce more stable ^{64}Ni. Fortunately, EC threshold energy of ^{64}Ni is 7.82 MeV, which is much higher than the electron chemical potential, so ^{64}Ni is stable in this environment. A similar analysis of other nuclides such as ^{56}Ni, ^{64}Ga, ^{60}Ni and ^{55}Co are also unstable, but their de-excited energies are quit different. And we find that the primary stable nuclides are ^{56}Fe, ^{64}Ni, ^{60}Fe, ^{55}Cr and ^{12}C, and the electron fraction changes to 0.45.

As the magnetic field decreases, both the densities and electron chemical potential will increase. However, we find that the electron chemical potential is still lower than the threshold energies of most nuclei (except ^{56}Fe, $^{56}\text{Fe} \rightarrow {}^{56}\text{Mn} \rightarrow {}^{56}\text{Cr}$ (^{56}Cr is stable)). This means that, although the dynamics on the magnetic field decay will lead to an increase in density and the electron chemical potential, the heat released via EC induced by magnetic field decay is very limited for the outermost crust, not as large as the previous estimation.

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