Influence of Magnetic Field Decay on Electron Capture in Magnetars

Jie Zhang$^{1,2}$ *

1. Institute of Theoretical Physics, China West Normal University, Nanchong 637009, China
2. Institute of Structure and Function, Chongqing University, Chongqing 400044, China

Received 2013 Jan 28; accepted 2013 May 26

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 the EC process near the outer crust and analyze 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 to the method

Magnetars, neutron stars with ultrastrong magnetic field, have been addressed by many researchers. In the 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. 2007; Götz et al. 2006). However, the considerable mechanism of the X-ray source is not clear up to now. Cooper et al. proposed a new heating mechanism in magnetar crusts (Cooper and Kaplan 2010). They argued that the magnetic pressure is comparable to electron degeneracy pressure in magnetar crust, 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, then which 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 the EC rate and the heat released in the EC process.

Here we introduce our quantitative results on this problem. We employs a magnetar model with typical mass $M = 1.4 \, M_{\odot}$ and radius $R = 10$ km (Thompson 2003). The previous researches show 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 is 0.1 km, which is much less than its radius. We assume
that the composition of the crust is the final products of the rp-process (Koike et
al. 2004). Of course, the products of rp-process may be quite different due to
the different accretion rate, ignition pressure of nuclear burning and so on. We
here choose Model 1a as an example, in which $^{64}\text{Zn}$ is the most abundant nuclides
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. Then we estimate the average
density $\bar{\rho}$ of crust by using the hydrostatic equilibrium condition.

In our work, shell model are adopted to calculate the EC rates. Strictly speak-
ing, precise rate must consider all transitions from the different initial state to dif-
ferent final state (Langanke and Martinez-Pinedo 2000; Pruet and Fuller 2003).
However, it is unlikely to make an accurate distribution for the all excited states
of each nucleus because the distribution of the high excited states is almost con-
tinuous (particularly for the heavier nuclei). For the case of 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 Ref.(Langanke and Martinez-Pinedo 1999; 2000)),
proton-neutron quasi-particle random phase approximation (pn-QRPA) theory (see
e. g., Nabi and Saijad 2008 ) or adopted the "Brink Hypothesis". LSSM’s cal-
culations indicate that "Brink hypothesis" is valid for the bulk of the GT strength
(Langanke and Martinez-Pinedo 1999). Since the surface temperature of magne-
tars are not high enough ($10^7-10^8$K), most of 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. The 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 neg-
ative threshold energy indicates the EC reaction does not require additional elec-
tronic energy; the positive threshold energy indicates that only the electrons whose
energy exceeds the corresponding threshold energies can take place EC reaction ef-
fectively, 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 nuclei, the EC rate is dom-
inant by the low energy transition. For the most abundant nuclide, $^{64}\text{Zn}$, weighted
mean of de-excited energy $\bar{Q}(^{64}\text{Zn}) = 0.42$MeV. Since the life of the magnetic field
is much larger than that of $^{64}\text{Zn}$, most of $^{64}\text{Zn}$ will quickly decay into $^{64}\text{Cu}$. Be-
cause the electron chemical potential is much higher than the EC threshold energy
of $^{64}$Cu, $^{64}$Cu will continue to capture electron quickly and produce more stable $^{64}$Ni. Fortunately, the EC threshold energy of $^{64}$Ni is 7.82MeV, which is much higher than the electron chemical potential, so $^{64}$Ni is stable in this environment. A similar analysis of other nuclides, we find $^{56}$Ni, $^{64}$Ga, $^{60}$Ni and $^{55}$Co are also unstable, but their de-excited energies are quite different. And we find 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 the electron electron chemical potential is still lower than the threshold energies of most nuclei (except $^{56}$Fe, $^{56}$Fe→$^{56}$Mn→$^{56}$Cr ($^{56}$Cr is stable)). This means that, although the dynamics on the magnetic field decay will lead to increased 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.

Acknowledgements
This work is supported by the National Natural Science Foundation of China (grant 11273020) and the Science Foundation of China West Normal University (grant 11B007).

References
Camilo, F., Ransom, S. M., Halpern, J. P., Reynolds, J. 2007, Astrophys. J. Lett., 666, L93
Cooper, R. L. and Kaplan, D. L., 2010, Astrophys. J. Lett. 708, L80
den Hartog, P. R., Kuiper, L. and Hermsen, W., 2008, Astron. Astrophys., 489, 263
Götz, D., Mereghetti, S., Tiengo, A., Esposito, P. 2006, Astron. Astrophys., 449, L31
Ibrahim, A. I., et al. 2004, Astrophys. J., 609, L21
Koike, O., Hashimoto, M., Kuromizu, R., Fujimoto, S. 2004, Astrophys. J., 603, 242
Langanke, K. and Martinez-Pinedo, G. 1999, Phys. Lett. B, 453, 187
Langanke, K. and Martinez-Pinedo, G. 2000, Nucl. Phys. A, 673, 481
Nabi, J. U. and Saijad M. 2008, Phys. Rev. C, 77, 055802
NNDC, 2012, http://www.nndc.bnl.gov
Pruet, J. and Fuller, G. M. 2003, Astrophys. J. Suppl. S., 149, 189
Thompson, C., Lyutikov, M., Kulkarni, S. R. 2002, Astrophys. J., 574, 332
Thompson, T. A. 2003, Astrophys. J., 585, L33