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Effects of ultra-strong magnetic field on electron capture rates of ^{55}Co and ^{56}Ni in the magnetar surrounding*

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Abstract: The electron capture rates of ^{55}Co and ^{56}Ni in the ultra-strong magnetic field at four typical temperature-density points have been calculated using the nuclear shell model and Landau energy levels quantized approximate correction. The results show that the electron capture rates of ^{55}Co and ^{56}Ni are increased greatly in the ultra-strong magnetic field, and even exceed two orders of magnitude in the range from 4.414×10^{13}G to 2.207×10^{17}G. The change rate of electron abundance, $\dot{Y}_{\rm e}$, of ^{55}Co and ^{56}Ni under the condition of B=4.414×10^{15}G in the magnetar surrounding has been calculated and discussed, the proportions of $\dot{Y}_{\rm e}$ of ^{55}Co and ^{56}Ni in the total $\dot{Y}_{\rm e}$ have been reduced by 50 percent in all more than the condition without a magnetic field.

Key words: electron capture, ultra-strong magnetic field, change rate of electron abundant

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1 Introduction

Weak interaction plays an important role in each stage of stellar evolution and many nuclear synthetic processes. Electron capture on iron group nuclei has been deeply researched for years. Weak interaction in the strong magnetic field was widely investigated by Fassio-Canuto shortly after the pulsar was discovered [1]. Now, the existence of an ultra-strong magnetic field in neutron stars is well proven by a large number of astronomical observations. Especially, the magnetic field strength of magnetars (neutron stars with an ultra-strong magnetic field) can reach 10^{13}–10^{18}G [2, 3]. A large number of iron group nuclei exist in the shell of neutron stars and magnetars. Neutron stars and magnetars provide an ideal laboratory for all kinds of nuclear physics processes.

Recent studies (Peng Qiu-He [4], Wang Kun [5]) show that in the ultra-strong magnetic field ($B\gg B_{\rm cr}$=4.414×10^{13}G), the Fermi surface of an electron will be elongated along the magnetic field direction from a Fermi spherical into a Landau cylinder; the Landau energy level is perpendicular to the direction of the magnetic field and is quantized. Now, the non-relativistic Landau energy levels theory has been revised [6]. Then, we found that the electron capture in the ultra-strong magnetic field did not decrease along with the increase of the magnetic field, but presented a trend of increase. The conclusion will affect the electron capture and β decay in the core of stars.

The electron capture of ^{55}Co and ^{56}Ni in the supernova has been calculated and discussed by Jameel-Un Nab et al. using the proton–neutron quasi-particle random phase approximation (pn-QRPA) theory [7], which expanded the pn-QRPA theory [8]. ^{55}Co and ^{56}Ni being high abundance ratios and high capture rates occupy a very important position, because the proportion of their $\dot{Y}_{\rm e}$, change rate of electron abundance, in $\dot{Y}_{\rm e(tot)}$ are 50% and 25%, respectively [9, 10].

Changes of the electron capture rates of ^{55}Co and ^{56}Ni with the ultra-strong magnetic field at four temperature-density points have been calculated using the nuclear shell model and Landau energy levels quantized approximate correction. Then, in the condition without magnetic field and B=4.414×10^{15} G, $\dot{Y}_{\rm e}$ of ^{55}Co and ^{56}Ni and their proportion in $\dot{Y}_{\rm e(tot)}$ have been calculated respectively and compared.

2 Electron capture in the ultra-strong magnetic field

The electron capture rate of a nucleus are given by [5]

$$\lambda=\lambda_0+\lambda_{\rm GT}=\ln2B_{\rm eff}f(Q_{00})+\ln2B_{\rm GT}f(Q_{00}-E_{\rm GT}),\quad(1)$$

where $B_{\rm eff}=1.65\times10^{-5}$. The function f is the phase space factor and, affected by the magnetic field [5], it can be

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expressed as [11–13]

$$f(Q_{\mathrm{if}})=\frac{b}{2}\sum_{n=0}^{\infty}q_{n0}\int_{q_n}^{\infty}(Q_{\mathrm{if}}+\varepsilon_n)^2F(Z,\varepsilon_n)f_{-\mathrm{e}}\mathrm{d}p_z$$

where $b=B/B_{\mathrm{cr}}$, $F(Z,\varepsilon_n)$ is the Coulomb wave correction, $f_{-\mathrm{e}}$ is the electron Fermi-Dirac distribution function, $\varepsilon_n=[1+P_z^2+(2n+1+\sigma)b]^{\frac{1}{2}}$, $\sigma=\pm1$, p_z is the electron momentum; E_{GT}, the resonance position, is defined by [11–13] $\mathrm{d}E_{\mathrm{GT}}=DE_1+DE_2+DE_3$, where DE_1 is the energy difference between orbitals that the new neutron occupies in the GT resonance state and the ground state (estimated using single particle energies), DE_2 is the particle-hole repulsion energy, which must be supplied to pull the neutron out of the daughter ground state and DE_3 is the cost to break a neutron pair if there is an even number of neutrons in the daughter nucleus. $B_{\mathrm{GT}}=10^{-3.596}M_{\mathrm{GT}}^2$, where M_{GT} is the GT transition matrix element at the resonance point. It can be expressed as [10]

$$M_{\mathrm{GT}}^2=\frac{1}{2}\frac{n_{\mathrm{i}}^{\mathrm{p}}n_{\mathrm{f}}^{\mathrm{h}}}{2j_{\mathrm{f}}+1}|M_{\mathrm{GT}}^{sp}|_{\mathrm{if}}^2, \tag{2}$$

where $n_{\mathrm{i}}^{\mathrm{p}}$ is the number of particles of the parent nucleus in the initial orbit, n_f^h is the number of holes of the daughter nucleus in the final orbit and $|M_{\mathrm{GT}}^{\mathrm{sp}}|_{\mathrm{if}}^2$ is the square of the single particle GT transition matrix element from the initial state to final state.

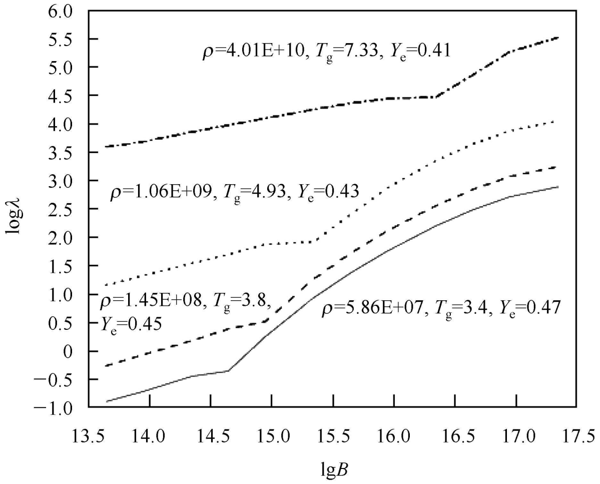

Fig. 1. (color online) Changes of the electron capture rates of ^{55}Co with the ultra-strong magnetic field in four typical conditions.

Figures 1 and 2 show respectively changes of the electron capture rates of ^{55}Co and ^{56}Ni with the ultra-strong magnetic field in four typical conditions. It can be seen from Fig. 1 and Fig. 2 that the electron capture rates of ^{55}Co and ^{56}Ni increased greatly in the ultra-strong magnetic field and even exceed two orders of magnitude for a given temperature-density point.

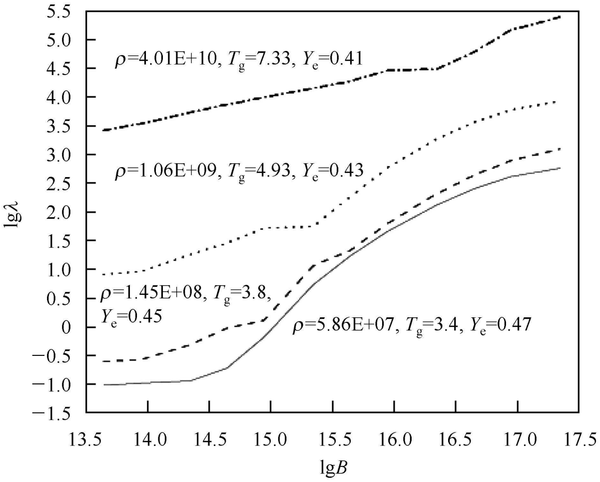

Fig. 2. (color online) Changes of the electron capture rates of ^{56}Ni with the ultra-strong magnetic field in four typical conditions.

3 Calculation and analysis of the change rate of Y_{e} in the ultra-strong magnetic field

Neither nuclei being high abundance ratios nor nuclei with high capture rates can determine the total electron capture rates in the magnetar surrounding; the total electron capture rate should be determined by all of the nuclei in the magnetar surrounding. For stellar evolution, the most important parameter is not Y_{e} (electron abundance), but $\dot{Y}_{\mathrm{e(tot)}}$, it can be given by [10, 14]

$$\dot{Y}_{\mathrm{e(tot)}}=(\mathrm{d}Y_{\mathrm{e}}/\mathrm{d}t)_{\mathrm{tot}}=\sum_K\frac{X_K}{A_K}\lambda_K, \tag{3}$$

where X_K and A_K are respectively the mass abundance and the mass number of the Kth kind of nuclei, λ_K is the electron capture rate of corresponding nuclei. So $\dot{Y}_{\mathrm{e}(K)}$, $\dot{Y}_{\mathrm{e}}$ for the Kth nucleus, can be given by [10]

$$\dot{Y}_{\mathrm{e}(K)}=(\mathrm{d}Y_{\mathrm{e}}/\mathrm{d}t)_K=\frac{X_K}{A_K}\lambda_K, \tag{4}$$

where X_K can be found through nuclear balance statistics. The proportion of $\dot{Y}_{\mathrm{e}(K)}$ in $\dot{Y}_{\mathrm{e(tot)}}$ can be given by [10]

$$R=\frac{\dot{Y}_{\mathrm{e}(K)}}{\dot{Y}_{\mathrm{e(tot)}}}, \tag{5}$$

M B Aufderheide et al. have given $\dot{Y}_\mathrm{e}$ of ^{55}Co and ^{56}Ni in the condition of ρ=4.32E+07, T_9=3.26E+00, Y_e=0.4850±0.0075 (no magnetic field), the R of ^{55}Co and ^{56}Ni are respectively 50% and 25% [9, 10].

Table 1 shows $\dot{Y}_\mathrm{e}$ of ^{55}Co and ^{56}Ni under the same condition (but B=4.414×10^{15} G), the proportions become respectively 8% and 17%, their total proportions have been reduced by 50 percent more than that without magnetic field.

Table 1. The R of ^{55}Co and ^{56}Ni (ρ=4.32E+07, T_9=3.26E+00, Y_e=0.4850±0.0075, B=4.414×10^{15}G).

^{A}Z	X_K	λ_K	$(\mathrm{d}Y_\mathrm{e}/\mathrm{d}t)_K$	R
^{55}Co	5.15E-02	2.06E+01	1.93E-02	7.57E-02
^{56}Ni	1.37E-01	1.77E+01	4.33E-02	1.70E-01
$(\mathrm{d}Y_\mathrm{e}/\mathrm{d}t)_\mathrm{tot}$=2.55E-01				

4 Conclusions

An ultra-strong magnetic field has a significant effect on the electron capture rates of ^{55}Co and ^{56}Ni, which can increase more than two orders of magnitude. At the same time, the magnetic field makes the R of ^{55}Co and ^{56}Ni decrease by 50 percent in all; the result shows that the contribution of the electron capture of ^{55}Co and ^{56}Ni to the $\dot{Y}_{\mathrm{e(tot)}}$ has reduced in the ultra-strong magnetic field.

The electron capture rates of ^{55}Co and ^{56}Ni play an important role in supernova explosion and neutrino cooling, which reduce the electronic degenerate pressure and the abundance of free protons, and decreases the iron core mass and entropy. Effects of the ultra-strong magnetic field on electron capture rates of ^{55}Co and ^{56}Ni have great value in studying the supernova explosion, neutrino cooling and the evolution of magnetic stars.

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