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A Research of Electron Capture for Nuclides in the Outer Crust of a Magnetar† ⋆

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Abstract In this paper, we investigate the effects of ultra-strong magnetic fields on the electron capture (EC) rates of $^{53,54,55}Fe$, by employing the approximation of Landau level quantization, and the nuclear shell model. Our results indicate that the EC rates increase about two orders of magnitude in the ultra-strong magnetic field compared with those in the weak-field limit. The rate of change of the electron fraction, $\dot{Y}_e$ for each kind of nuclide and the total $\dot{Y}_e$ in the conditions of weak-field approximation and $B = 4.414 \times 10^{15}$ Gs have been calculated, respectively, and their differences under the two conditions exceed three orders of magnitude generally. These conclusions will play an important role in the future study of magnetar evolution.

Key words stars: magnetars—stars: evolution—stars: magnetic field—stars: interiors—methods: numerical

1. INTRODUCTION

Magnetars are one kind of compact celestial bodies with ultra-strong magnetic fields, and belong to a particular kind of neutron stars. Historically, the megnetars are classified into two sorts, which are discovered independently owing to their distinct forms of high-energy radiations. One sort of magnetars are the soft gamma-ray repeaters (SGRs), and another sort of magnetars are the abnormal X-ray pulsars (AXPs)[1]. The weak interaction (especially the electron capture) plays an important role in the neutrino cooling and magnetar evolution, the high-abundance iron-family nuclides exist in the outer crusts of magnetars, the extra-strong magnetic field existed in the magnetar provides an ideal environment for the study

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of electron capture (EC). Hence the study of EC in the outer crust of a magnetar is very important[2−3].

The studies of EC for the iron-family nuclides have lasted for many years. The early studies suggested that the ultra-strong magnetic field has a very large influence on the EC, and that the EC rate decreases apparently with the strength of magnetic field. However, the recent studies (Gao et al.[4] and Wang et al.[5]) indicate that under the ultra-strong magnetic field ($B \gg B_{cr}$, $B_{cr} = 4.414 \times 10^{13}$ Gs, called as the quantum critical magnetic field, in which the synchrotron radiation energy of an electron is equivalent to the energy corresponding to its rest mass), the Fermi surface will be elongated along the direction of magnetic field from a Fermi sphere to a Landau column, the energy level is perpendicular to the direction of magnetic field, and it will be quantized. In this case, the non-relativistic Landau energy-level theory should be revised[4,6]. Then, we find that as the magnetic field enhances, the EC rate does not reduce but tends to increase. This conclusion will affect the EC and β decay in stellar interiors. The EC rate has significant influences on the origin and evolution of the magnetic field of neutron stars. The ultra-strong magnetic field increases with the increasing electron Fermi energy $E_{\rm F,e}$, and therefore induces the EC reaction in the interiors of magnetars (mainly in the outer nuclei of magnetars)[6]. Considering the importance of iron-family nuclides, the effects of ultra-strong magnetic fields on the ECs of ^{53,54,55}Fe are analyzed in this paper.

The total EC rate in the stellar environment is determined by neither the high-abundance nuclides nor the nuclides of high EC rates, it is determined jointly by all nuclides under the stellar environment. For stellar evolution, the most important parameter is not the electron fraction, but its rate of change. Aufderheide et al.[7] have studied the total rate of change of electron fraction, but not concerned with the effect of ultra-strong magnetic field on the rate of change of electron fraction. In this paper we have studied the EC in the outer crust of a magnetar. This paper is organized as follows: in Sec.2 we introduce the calculation formulae of the EC rate and the rate of change of electron fraction; in Sec.3 we calculate and analyze the EC rate and the rate of change of electron fraction for the nuclides in the outer crust of a magnetar; in Sec.4 we give the main conclusions.

2. THE EC RATE AND THE RATE OF CHANGE OF ELECTRON FRACTION IN ULTRA-STRONG MAGNETIC FIELDS

In the following we briefly introduce the calculation method of the EC rate. When the nuclide transits from the initial state i to the final state f the total EC rate is[8]

$$\lambda_i = \sum_f \lambda_{if} = \sum_f \ln 2 B_{if} f(Q_{if}) \,, \tag{1}$$

in which $B_{if} = 10^{-3.596} M_{if}^2$ (M_{if} is the element of Gamow-Teller (G-T) transition matrix), $f(Q_{if})$ is the phase-space factor, Q_{if} is the threshold value of EC reaction, which can be