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Exotic Nuclei in the Crust of Magnetars*

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Abstract. We have determined the sequence of exotic nuclei expected to be present in the outer crust of a magnetar. For this purpose, we have made use of experimental atomic mass measurements from the 2012 Atomic Mass Evaluation, complemented with the latest microscopic atomic mass models from the Brussels-Montreal group.

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1 Introduction

At the end point of stellar evolution, neutron stars are among the strongest magnets in the Universe (see, e.g., [1]). In particular, magnetic fields up to about $10^{16} - 10^{17}$ G could be generated in hot newly-born neutron stars [2]. Soft gamma-ray repeaters and anomalous X-ray pulsars are believed to be the best candidates of these so called magnetars (see, e.g., [3] for a review). Their surface magnetic fields, as inferred from spin-down and spectroscopic studies, are estimated to be of order $10^{14} - 10^{15}$ G (see, e.g., [4] for estimates of the magnetic field strengths of these peculiar objects, and references therein). Numerical simulations have shown that these stars may have internal magnetic fields, as strong as $\sim 10^{18}$ G [5–7].

The interior of a magnetar is composed of four main regions: i) the outer crust primarily composed of pressure ionized atoms arranged in a regular crystal lattice and embedded in a highly degenerate electron gas [8–10], ii) the inner crust at densities $\gtrsim 4 \times 10^{11}$ g/cm^3 where nuclei coexist with a neutron liquid [11], iii) the outer core at densities above $\sim 10^{14}$ g/cm^3 made of a uniform mixture of nucleons and leptons [12, 13], and iv) the inner core whose composition remains very uncertain.

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In our previous calculations of the outer crust of a magnetar [8–10], we determined its composition using a preliminary unpublished version of the Atomic Mass Evaluation complemented with the microscopic atomic mass model HFB-21 [14]. In this work, we present new results using the experimental data from the Atomic Mass Evaluation published in 2012 [15]. For the atomic masses that have not yet been been measured, we have applied the latest atomic mass models from the Brussels-Montreal group [16, 17]. We briefly review the microscopic description of the outer crust in Section 2 before discussing the results in Section 3.

2 Microscopic Model of Magnetar Outer Crusts

The model of magnetar crusts we adopt here is essentially the same as the one we have used in our previous works. We will therefore only review the main assumptions and emphasize the differences (details can be found, e.g., in [10]).

The outer crust is assumed to be made of fully ionised atoms arranged in a body-centered cubic lattice at zero temperature. In addition, the outer crust is supposed to contain homogeneous crystalline structures, i.e. structures made of only one type of nuclides with proton number Z and atomic number A. The values of Z and A in each layer of pressure P are found by minimising the Gibbs free energy per nucleon

$$g = \frac{\mathcal{E} + P}{n} \tag{1}$$

with n the average nucleon number density and $\mathcal{E}$ the average energy density given by

$$\mathcal{E} = n_N M'(Z, A) + \mathcal{E}_e + \mathcal{E}_L \tag{2}$$

where $n_N = n/A$ is the number density of nuclei, $M'(Z, A)$ their mass (including the rest mass of nucleons and Z electrons), $\mathcal{E}_e$ – the energy density of electrons after subtracting out the electron rest mass energy density, and $\mathcal{E}_L$ – the lattice energy density.

The nuclear mass $M'(Z, A)$ can be obtained from the atomic mass $M(Z, A)$ after subtracting out the binding energy of the atomic electrons (see Eq.(A4) of [18]). As in our previous works [8–10], we ignore here the change of nuclear masses caused by the magnetic field. According to recent fully self-consistent relativistic mean-field calculations [19], magnetic field strengths $B \lesssim 10^{17}$ G do not have any substantial impact on nuclear masses and therefore on the composition of the outer crust. We use the most recent experimental atomic mass data from the 2012 Atomic Mass Evaluation (AME) [15]. For the masses that have not yet been measured, we employ the microscopic atomic mass models HFB-24 [16] and HFB-27* [17]. Both are based on the self-consistent Hartree-Fock-Bogoliubov method (see, e.g., [20] for a review), but using two different kinds of Skyrme effective nucleon-nucleon interactions: a standard interaction in the case of HFB-27*, and a generalized interaction in the case of HFB-24 (the normal part including terms that are both density- and momentum-dependent [21], whereas the pairing interaction was derived from microscopic calculations [22]). These models yield an excellent fit to essentially all available experimental atomic mass measurements from the 2012 AME, HFB-27* [17] being slightly more accurate with a root-mean square deviation of 512 keV, as compared to 549 keV for HFB-24 [16].

In the presence of a strong magnetic field, the electron motion perpendicular to the field is quantized into Landau levels (see, e.g., Chapter 4 of [1]). The magnetic field strength is conveniently measured in terms of the critical magnetic field B_c given by

$$B_c = \frac{m_e^2 c^3}{e\hbar} \simeq 4.4 \times 10^{13}\,\mathrm{G}\,. \tag{3}$$

We neglect the small electron anomalous magnetic moment and electron polarization effects (see, e.g., Chapter 4 of Ref. [1] and references therein), we treat electrons as a relativistic Fermi gas. According to the Bohr-van Leeuwen theorem [24,25], the lattice energy density is not affected by the magnetic field apart from a negligibly small contribution due to the quantum zero-point motion of ions [26]. The expressions of $\mathcal{E}_e$ and $\mathcal{E}_L$ can be found in [10].

3 Composition of Magnetar Crusts

We have calculated the composition of magnetar crusts for a strongly quantizing magnetic field of strength $B_\star \equiv B/B_c = 2000$. Results are summarized in Table 1. Experimental atomic mass data allow the determination of the crustal composition down to a depth where the pressure is about 3.31×10^{-4} MeV fm^{-3}. Although the mass of ^{130}Cd is known experimentally, the pressure above which it disappears remains uncertain, ranging from 3.69×10^{-4} for HFB-24 to 3.85×10^{-4} MeV fm^{-3} for HFB-27*. The sequence of nuclides predicted by the HFB-24 atomic mass model at higher pressures is the same as that previously found with the HFB-21 atomic mass model (see Table 2 in [9]). Both models are based on the same kind of generalized Skyrme interactions, but they differ in the experimental atomic mass data to which they were fitted: the 2003 AME [27] for HFB-21 vs the 2012 AME [15] for HFB-24. On the other hand, some differences are observed between the results obtained with HFB-24 and those obtained with HFB-27*. The nuclei ^{121}Y and ^{124}Sr are predicted to be present in the magnetar crust by the model HFB-24 but not by the model HFB-27*. Moreover, the model HFB-27* predicts the existence of ^{124}Zr contrary to the model HFB-24. These discrepancies arise from the uncertainties in the masses of neutron-rich nuclei, which amount to $\sim 1-2$ MeV for the nuclei expected to be found in the dense region of the outer crust of a magnetar (see Table 2).

Table 1. Sequence of equilibrium nuclides with increasing depth in the outer crust of a magnetar for two different microscopic atomic mass models. The magnetic field strength is $B_\star = 2000$. The nuclides with experimentally measured masses are indicated in boldface. The maximum pressure at which each nuclide can be found is indicated in parenthesis in units of MeV fm^{-3}.

HFB-24	HFB-27*
^{56}**Fe** (3.12×10^{-7})	^{56}**Fe** (3.12×10^{-7})
^{62}**Ni** (1.23×10^{-5})	^{62}**Ni** (1.23×10^{-5})
^{88}**Sr** (2.68×10^{-5})	^{88}**Sr** (2.68×10^{-5})
^{86}**Kr** (7.06×10^{-05})	^{86}**Kr** (7.06×10^{-05})
^{84}**Se** (1.46×10^{-4})	^{84}**Se** (1.46×10^{-4})
^{82}**Ge** (2.44×10^{-4})	^{82}**Ge** (2.44×10^{-4})
^{132}**Sn** (2.56×10^{-4})	^{132}**Sn** (2.56×10^{-4})
^{80}**Zn** (3.31×10^{-4})	^{80}**Zn** (3.31×10^{-4})
^{130}**Cd** (3.69×10^{-4})	^{130}**Cd** (3.85×10^{-4})
^{128}Pd (4.98×10^{-4})	^{128}Pd (5.07×10^{-4})
^{126}Ru (5.78×10^{-4})	^{126}Ru (5.81×10^{-4})
^{124}Mo (7.72×10^{-4})	^{124}Mo (7.99×10^{-4})
^{122}Zr (8.83×10^{-4})	^{122}Zr (8.94×10^{-4})
^{121}Y (8.98×10^{-4})	–
–	^{124}Zr (9.72×10^{-4})
^{120}Sr (9.82×10^{-4})	^{120}Sr (9.83×10^{-4})
^{122}Sr (1.11×10^{-3})	^{122}Sr (1.15×10^{-3})
^{124}Sr (1.15×10^{-3})	–

In spite of the differences in the composition, both models predict the occurence of neutron drip at the same pressure $P_{\rm drip} \simeq 1.15 \times 10^{-3}$ MeV fm^{-3} (this is also the same pressure as that obtained with the model HFB-21, see Fig.1 of [10]). This result can be easily understood. Indeed, the pressure depends mainly on the binding energy a_v of symmetric nuclear matter and on the symmetry energy coefficient J, as discussed in [10], and these two coefficients are essentially the same for the two atomic mass models: $J = 30$ MeV for both models, and the values of a_v are -16.048 MeV for HFB-24 vs -16.051 MeV for HFB-27*.

Table 2. Mass excesses (in MeV) of some nuclei of relevance for the crust of magnetars, as predicted by two different microscopic atomic mass models.

Nucleus	HFB-24	HFB-27*
^{121}Y	32.990	35.009
^{124}Zr	33.840	34.979
^{120}Sr	46.504	48.271
^{122}Sr	61.452	63.254
^{124}Sr	77.338	79.470

4 Conclusion

We have calculated the sequence of exotic nuclei in the outer crust of a magnetar using the data from the 2012 Atomic Mass Evaluation complemented with the Hartree-Fock-Bogoliubov atomic mass models HFB-24 and HFB-27*. We have found that these two models predict the same composition for the outermost layers of the crust, but differ in the shallowest region due to uncertainties in the masses of nuclides with $Z \sim 40$ and $A \sim 120$. On the other hand, neutron drip occurs at the same pressure for both models.

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