Nuclear structure in strong magnetic fields: nuclei in the crust of a magnetar

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Objective

- What is the effect of the magnetic field on the composition of a neutron star?

Previous studies:

- Several studies on EOS
- No studies for the pasta phase (that I am aware of)
- Only qualitative results on nuclei

Objective

1. What is the minimum field that is able to significantly alter the nuclear structure?
2. Is this field low enough to be found in a significant proportion of neutron stars or magnetars?
3. Is this effect big enough to influence astrophysically relevant situations and processes, e.g. neutron star outer crust composition or final element abundances in nucleosynthesis scenarios?

Orders of Magnitude

≈ 0.5 G	earth's magnetic field
$\approx 10^4$ G	magnetic resonance
$\approx 10^9$ G	atomic cigars and pancakes
$4\ 10^{13}$ G	Electron critical field
$10^{12} - 10^{14}$ G	neutron stars
$\approx 10^{16}$ G	largest observed in magnetars
$10^{17} - 10^{18}$ G	largest in magnetar (theory)
$\approx 10^{20}$ G	Proton critical field

Orders of Magnitude

$$\Delta_{so} \approx \mu_N B \rightarrow B \approx 10^{16} - 10^{17} G$$

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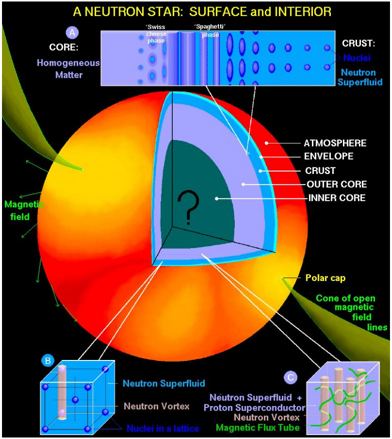
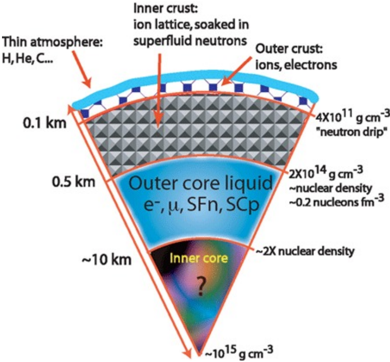
Magnetars



A NEUTRON STAR: SURFACE and INTERIOR
A
CORE:
Homogeneous Matter
'Swiss cheese' phase
'Spaghetti' phase
CRUST:
Nuclei
Neutron Superfluid
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Magnetic field
Polar cap
Cone of open magnetic field lines
B
Neutron Superfluid
Neutron Vortex
Nuclei in a lattice
C
Neutron Superfluid + Proton Superconductor
Neutron Vortex
Magnetic Flux Tube



Thin atmosphere: H, He, C...
Inner crust: ion lattice, soaked in superfluid neutrons
Outer crust: ions, electrons
0.1 km
4X10^11 g cm^-3 "neutron drip"
0.5 km
Outer core liquid e⁻, μ, SFn, SCp
2X10^14 g cm^-3 ~nuclear density ~0.2 nucleons fm^-3
~10 km
Inner core
?
~2X nuclear density
~10^15 g cm^-3

The model: overview

The model:

- Based on relativistic mean-field (with NL3)
- Simplest self-consistent formulation
- Includes orbital and Pauli-spin coupling to the magnetic field

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Consequences of the breaking of TR symmetry by the magnetic field

- Currents
- Deformation

The model: details

Standard RMF Lagrangian:

$$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_m + \mathcal{L}_i$$

$\mathcal{L}_i$ includes two new terms:

- Coupling to orbital motion (only protons)

$$\mathcal{L}_{BO} = -e\bar{\psi}\frac{1}{2}(1-\tau_3)\gamma^\mu A_\mu^{(e)}\psi$$

- Coupling to magnetic moments (protons and neutrons)

$$\begin{aligned} \mathcal{L}_{BM} &= -i\tau_3\bar{\psi}\chi_{\tau_3}^{(e)}\psi \\ \chi_{\tau_3}^{(e)} &= \frac{1}{4}|\kappa_{\tau_3}|\gamma_0\sigma_{\mu\nu}F^{(e)\mu\nu} \\ \kappa_{\tau_3} &= \frac{1}{2}\mu_N g_{\tau_3} \\ \sigma_{\mu\nu} &= [\gamma_\mu, \gamma_\nu] \end{aligned}$$

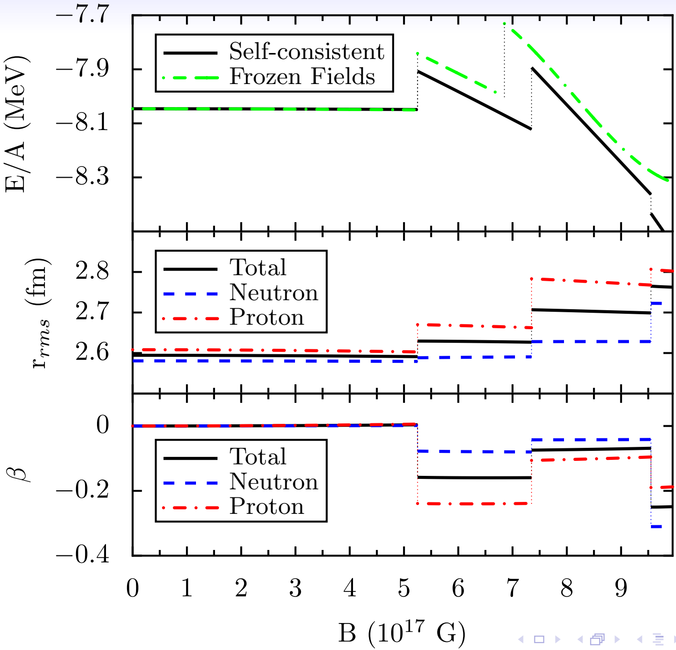
The model: details

- Energy density functional

$$E_{\boldsymbol{B}}[\hat{\rho},\phi] = \mathrm{Tr}\left[\left(\boldsymbol{\alpha}\left(-i\boldsymbol{\nabla} - e\boldsymbol{A}^{(e)}\right) + \beta(m+\chi^{(e)}_{\tau_3})\right)\hat{\rho}\right] + \sum_m \mathrm{Tr}\left[\left(\beta\,\boldsymbol{\Gamma}_m\phi_m\right)\hat{\rho}\right] \pm \sum_m \int d^3r \left[\frac{1}{2}(\partial_\mu\phi_m)^2 + \frac{1}{2}m_m^2\phi_m^2\right], \qquad (1)$$

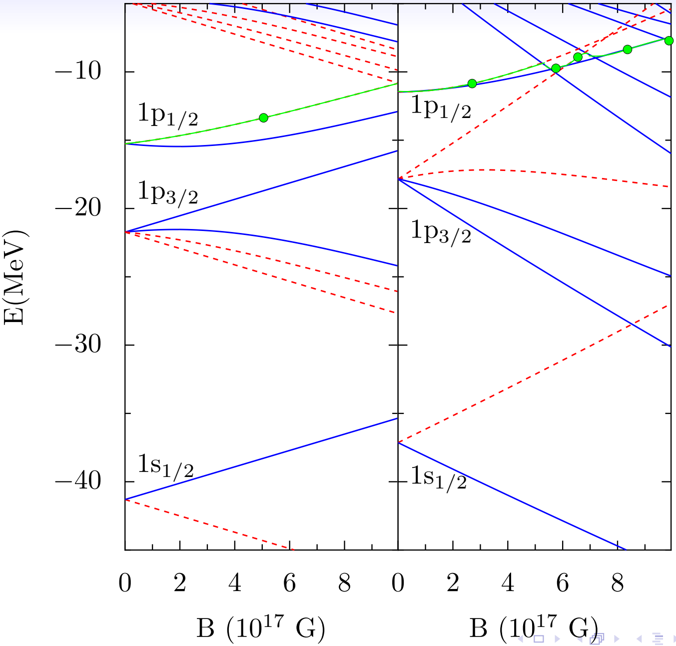
- Constant magnetic field $\boldsymbol{B}$ along positive z-axis
- Axial deformation, symmetry axis along $\boldsymbol{B}$
- Symmetric gauge $\rightarrow$ $\boldsymbol{A} = i\left(-\frac{r|\boldsymbol{B}|}{2}e^{-i\theta}, +\frac{r|\boldsymbol{B}|}{2}e^{i\theta}, 0\right)_{\mathrm{stb}}$

Example: ^{16}O



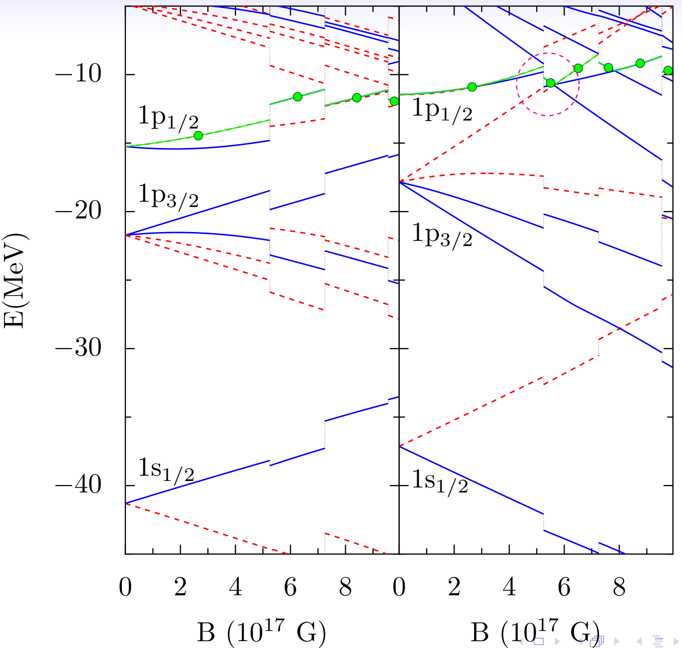
−7.7
−7.9
−8.1
−8.3
E/A (MeV)
Self-consistent
Frozen Fields
2.8
2.7
2.6
r_rms (fm)
Total
Neutron
Proton
0
−0.2
−0.4
β
Total
Neutron
Proton
0 1 2 3 4 5 6 7 8 9
B (10^17 G)

Example: ^{16}O



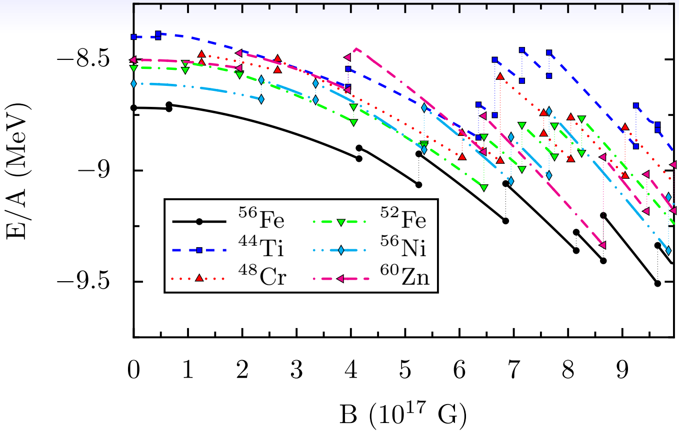
E(MeV)
−10
−20
−30
−40
1p1/2
1p3/2
1s1/2
1p1/2
1p3/2
1s1/2
0
2
4
6
8
0
2
4
6
8
B (10^17 G)
B (10^17 G)

Example: ^{16}O



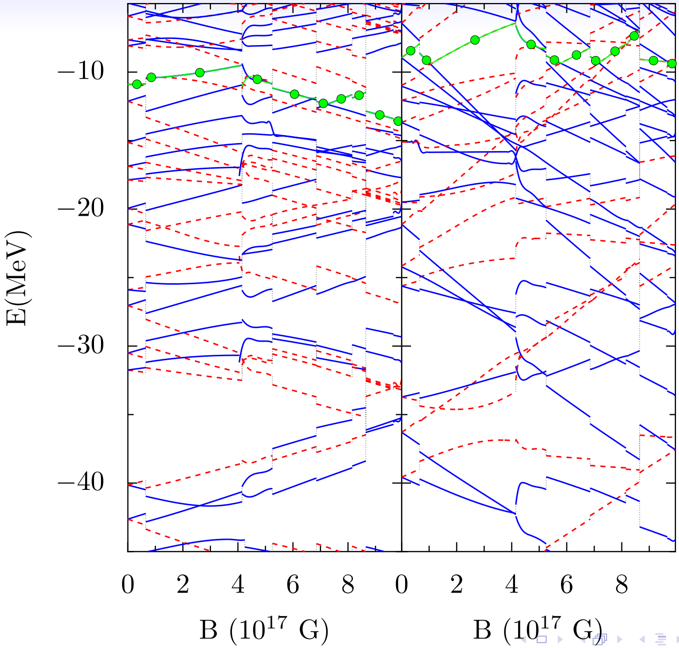
−10
−20
−30
−40
E(MeV)
1p1/2
1p3/2
1s1/2
1p1/2
1p3/2
1s1/2
0
2
4
6
8
0
2
4
6
8
B (10^17 G)
B (10^17 G)

^{56}Fe

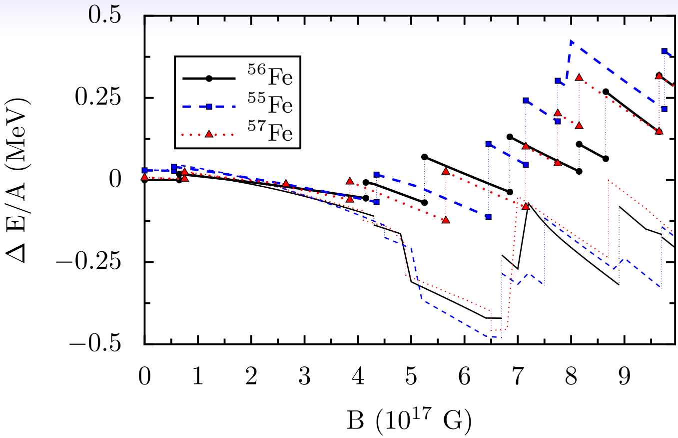


−8.5
−9
−9.5
E/A (MeV)
0
1
2
3
4
5
6
7
8
9
B (10^17 G)
56Fe
44Ti
48Cr
52Fe
56Ni
60Zn

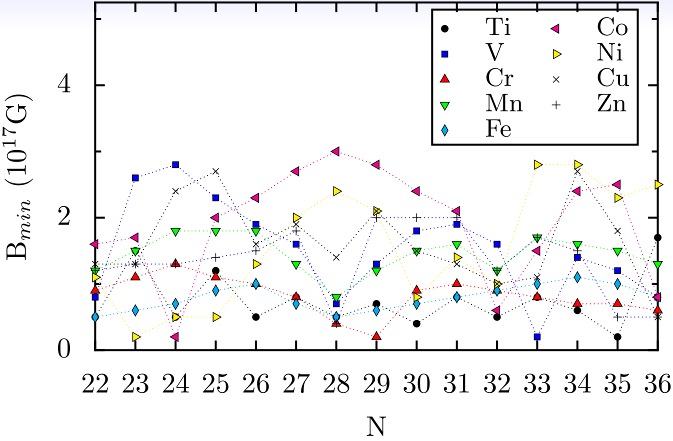
Sample of crust nuclei around ^{56}Fe



Sample of crust nuclei around ^{56}Fe



Minimum Magnetic Field



Conclusions and perspectives

- Minimum fields are of the order of 10^{17}G
- Require a self-consisten formulation
- Minimum field depends a lot on the considered nucleus
- Changes in BE: from few tenths of keV to hundreths of keV