Electron captures and neutron emissions in magnetic white dwarfs and magnetars

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1869
БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ

comp star

Rila, 24 June 2015

Prelude

Soon after the discovery of the neutron (predicted by Rutherford in 1920) by James Chadwick in February 1932, it was realized that **at the high densities prevailing in stars matter is very neutron rich.**
Sterne, Mon. Not. R. Astron. Soc. 93, 736 (1933).

In December 1933, during a meeting of the American Physical Society at Stanford, Wilhelm Baade and Fritz Zwicky predicted the existence of **neutron stars** during core-collapse **supernovae**.
Phys. Rev. 45 (1934), 138

Prelude

Baade and Zwicky were apparently unaware of the work about the maximum mass of white dwarfs. This is Gamow who first made the connection in 1939 (*Phys. Rev.55, 718*). At a conference in Paris in 1939, Chandrasekhar also pointed out

"If the degenerate core attains sufficiently high densities, the protons and electrons will combine to form neutrons. This would cause a sudden diminution of pressure resulting in the collapse of the star to a neutron core."

Conférences du Collège de France, Colloque International d'Astrophysique III, 17-23 Juillet 1939, (Paris, Hermann, 1941), pp 41-50.

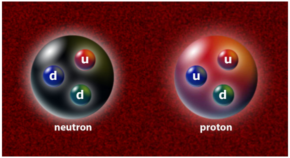
Electron captures and neutron emissions play a crucial role in dense astrophysical environments.

Outline

1. Overluminous type Ia supernovae and super Chandrasekhar magnetic white dwarfs
2. Strongly magnetized neutron stars (magnetars)

Why neutronization in dense matter?

A neutron in vacuum is unstable
because $m_n > m_p$
(a proton has a lower energy).



However, **neutrons are stable in cold dense matter** due to electron captures by nuclei ${}^A_Z\mathrm{X} + e^- \rightarrow {}^A_{Z-1}\mathrm{Y} + \nu_e$.

Ignoring electron-ion interactions, this reaction can occur if the electron Fermi energy μ_e exceeds the threshold value $\mu_e^\beta = M(A, Z-1)c^2 - M(A, Z)c^2$.

For ultrarelativistic degenerate electrons $\mu_e \approx \hbar c(3\pi^2 n_e)^{1/3}$.

The density at the onset of neutronization is thus given by

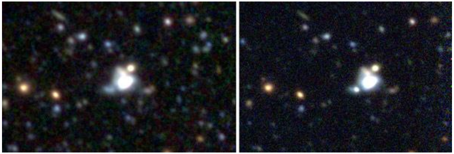
$$\rho \approx \frac{A}{Z}\frac{m}{3\pi^2}\left(\frac{\mu_e^\beta}{\hbar c}\right)^3 \gtrsim 10^7 \ \mathrm{g/cm^3}$$

Type Ia supernova

Type Ia supernovae

White dwarfs are generally thought to be the progenitors of type Ia supernovae: as the white-dwarf mass gets close to the Chandrasekhar limit $\sim 1.4 M_{\odot}$, the ignition of carbon fusion reactions leads to the disruption of the white dwarf.

Overluminuous type SNIa



However, a few SNIa like SN2003fg are **overluminuous** implying a white dwarf mass $> 2M_\odot$!

Howell et al., Nature 443, 308 (2006).

Because SNIa have been used as standard candles in cosmology, **measurements of the acceleration of the expansion could be spoiled**.

Two different kinds of scenarios have been proposed:

1. single-degenerate progenitor
   - rapidly differentially rotating white dwarf
   - strongly magnetized white dwarf
2. double-degenerate progenitors
   - white-dwarf merger

Hillebrandt et al., Front. Phys. 8, 116 (2013).

Maoz, Mannucci,Nelemans, arXiv:1312.0628

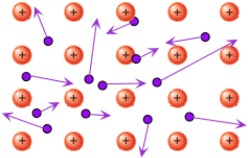
Super-Chandrasekhar Magnetic White Dwarfs

Recently, an Indian group proposed that overluminuous SNIa are triggered by the explosion of **white dwarfs endowed with ultra strong magnetic fields**.

Das and Mukhopadhyay, PRL 110, 071102 (2013).

The possibility of strongly magnetized white dwarfs is not new:

G. A. Shul'man, Sov. Astron. 20, 689 (1976).



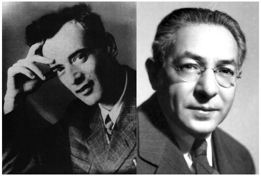
In the core of a white dwarf, electrons are free and highly degenerate. They provide the necessary pressure to prevent the gravitational collapse of the star.

R. H. Fowler, MNRAS 87, 114 (1926).

In a strong magnetic field, the electron gas is much less compressible thus allowing for more massive stars.

Electrons in strongly quantizing magnetic fields

In a strong $\vec{B}$ (let's say along z), the **electron motion perpendicular to the field is quantized** into discrete Landau (actually Rabi!) levels.



$$e_\nu = \sqrt{c^2 p_z^2 + m_e^2 c^4 (1 + 2\nu B_\star)}$$
where $\nu = 0, 1, ...$ and $B_\star = B/B_c$
with $B_c = \dfrac{m_e^2 c^3}{\hbar e} \simeq 4.4 \times 10^{13}$ G.

Rabi, Z.Phys.49, 507 (1928).

The magnetic field is strongly quantizing if $\nu_{\max} = 0$.

This occurs if $\rho < \rho_B = \dfrac{A}{Z}\dfrac{m}{\lambda_e^3}\dfrac{B_\star^{3/2}}{\sqrt{2}\pi^2} \approx 2.1 \times 10^6 \dfrac{A}{Z} B_\star^{3/2}$ g cm^{-3} and
$T < T_B = \dfrac{m_e c^2}{k_B} B_\star \approx 5.9 \times 10^9 B_\star$ K.

In this regime, **the equation of state is very stiff** ($P \propto \rho^2$ instead of $P \propto \rho^{4/3}$ in the absence of magnetic fields).

Maximum mass of strongly magnetized white dwarfs

Using the well-known solutions of the Lane-Emden equations (hydrostatic equilibrium), it is a simple matter to determine the maximum mass of strongly magnetized white dwarfs:

$$M_{\rm max} = \left(\frac{Z}{A}\right)^2 \left(\frac{\pi\hbar c}{G}\right)^{3/2} \frac{1}{m^2} \simeq 2.6 \left(\frac{Z/A}{0.5}\right)^2 M_\odot$$

Das and Mukhopadhyay, PRL 110, 071102 (2013).

This result is based on the following assumptions:

- gravity is Newtonian
- $\vec{B}$ is uniform
- the star is spherical
- the central density is $\rho_B = \frac{A}{Z}\frac{m}{\lambda_e^3}\frac{B_\star^{3/2}}{\sqrt{2}\pi^2}$ $(\nu_{\rm max} = 0)$
- the magnetic force is negligible compared to gravity.

Global stability

However, these assumptions are not valid! For a stellar configuration to be stable, Chandrasekhar and Fermi showed a long time ago that we must have $E_{\rm mag} < |E_{\rm grav}|$.

For the solution found by Das and Mukhopadhyay, we find that

$$\frac{E_{\rm mag}}{|E_{\rm grav}|} = \frac{\pi^3}{18\alpha} \simeq 236!$$

Chamel, Fantina, Davis, Phys.Rev.D88, 081301(R) (2013)
Coelho et al., Astrophys. J.794, 86 (2014)

Therefore, spherical white dwarfs endowed with uniform magnetic fields are globally unstable.

But this does not necessarily rule out the existence of super Chandrasekhar white dwarfs with non-uniform magnetic fields.
Bera & Bhattacharya, MNRAS 445, 3951 (2014).

Local stability

On the other hand, the local stability of such putative strongly magnetized super-Chandrasekhar white dwarfs would be limited by the onset of electron captures by nuclei

$$^{A}_{Z}X + e^- \rightarrow^{A}_{Z-1} Y + \nu_e \,.$$

In the strongly quantizing regime ($\nu_{\rm max} = 0$), the electron Fermi energy is given by $\mu_e \approx 2\pi^2 m_e c^2 \lambda_e^3 n_e / B_\star$.

Electrons can thus be captured whenever

$$\rho \geq \rho_\beta(A, Z, B_\star) \approx \frac{A}{Z} \frac{m B_\star}{2\pi^2 \lambda_e^3} \frac{\mu_e^\beta(A, Z)}{m_e c^2} \,,$$

$$\mu_e^\beta = M(A, Z-1)c^2 - M(A, Z)c^2.$$

Chamel, Fantina, Davis, Phys.Rev. D88, 081301(R) (2013)

Upper limit on the magnetic field strength

If $\rho_\beta(A, Z, B_\star) < \rho_B(A, Z, B_\star)$ at the center of the star, or equivalently $B_\star > B_\star^\beta(A, Z)$, the star will become locally unstable against electron captures. **The onset of pycnonuclear fusion reactions $2^A_Z X \rightarrow^{2A}_{2Z} Y$ further limits the stability.**

$^A_Z X$	$B_\star^\beta$
^{4}He	873
^{12}C	387
^{16}O	242
^{20}Ne	116
^{21}Ne	78
^{22}Ne	262

with pycnonuclear fusions

$^{2A}_{2Z} X$	$B_\star^\beta$
^{24}Mg (^{12}C+^{12}C)	74
^{32}S (^{16}O+^{16}O)	9.8
^{40}Ca (^{20}Ne+^{20}Ne)	6.5

Chamel, Fantina, Davis, Phys.Rev.D88, 081301(R) (2013)
Chamel et al.,Phys.Rev.D90,043002(2014)

$B_\star^\beta$ is much weaker than the magnetic field considered by Das and Mukhopadhyay in their calculations (up to $B_\star \sim 10^4$).

Electron capture rates and metastability

The onset of electron captures does not necessarily mean that ultramagnetic white dwarfs are unstable: they could still be metastable if electron capture rates are low enough.

We have thus computed those rates using the self-consistent finite temperature Skyrme Hartree-Fock+RPA method:

Species	rate (s^{-1})	
	$B_\star = 2 \times 10^3$	$B_\star = 2 \times 10^4$
^{12}C	3.5×10^3	6.2×10^4
^{16}O	4.4×10^2	1.3×10^4
^{20}Ne	1.3×10^4	1.1×10^5
^{22}Ne	2.8×10^3	4.5×10^4
^{24}Mg	3.6×10^4	2.6×10^5
^{32}S	1.2×10^5	6.8×10^5
^{40}Ca	1.7×10^4	2.2×10^5
^{44}Ca	4.7×10^3	8.7×10^4
^{56}Fe	1.3×10^5	7.9×10^5

Chamel et al.,Phys.Rev.D90,043002(2014)

This shows that putative ultra-massive and strongly magnetized white dwarfs considered by Das and Mukhopadhyay are highly unstable.

Onset of electron capture in magnetized matter

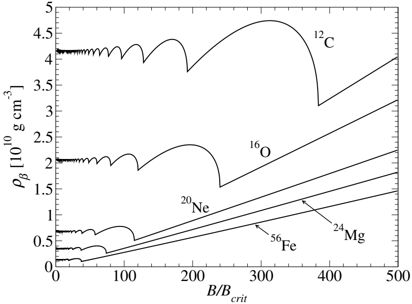
On the other hand, the magnetic field could be stronger if the density at the center of the star is higher than ρ_B, as suggested by recent calculations.
Bera & Bhattacharya, MNRAS 445, 3951 (2014).

Strong magnetic fields up to $\sim 10^{18}$ G could also potentially exist in so called **strange dwarfs**, i.e. white dwarfs with a core made of deconfined up, down and strange quarks.
Glendenning, Kettner, Weber, PRL 74, 3519 (1995)
Chatterjee et al., MNRAS 447, 3785 (2015)

We have recently reexamined the onset of electron captures for any magnetic field strength, taking into account electron-ion interactions.
Chamel & Fantina, submitted to Phys. Rev. D

Onset of electron capture in magnetized matter

The threshold density exhibits typical quantum oscillations:



Chamel & Fantina, submitted to Phys. Rev. D

In the strongly quantizing regime

$$\rho_\beta \approx \frac{m B_\star \mu_e^\beta}{2\pi^2 m_e c^2 \lambda_e^3}$$

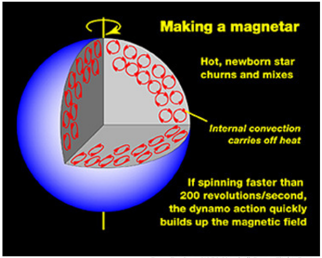
$$P_\beta \approx \frac{B_\star \mu_e^{\beta\,2}}{4\pi^2 \lambda_e^3 m_e c^2}.$$

Electron-ion interactions yield corrections of order $\alpha = e^2/\hbar c$.

The stability of magnetic white dwarfs may thus change with time as the magnetic field decays.

Strongly magnetized neutron stars (magnetars)

Theory of magnetars

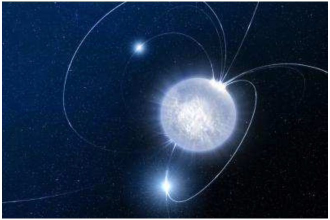


Dave Dooling, NASA Marshall Space Flight Center

Duncan and Thompson showed that strong magnetic fields $\sim 10^{16}$ G can be generated via dynamo effects in hot newly-born neutron stars with initial periods of a few milliseconds.
Thompson & Duncan, ApJ 408, 194 (1993).

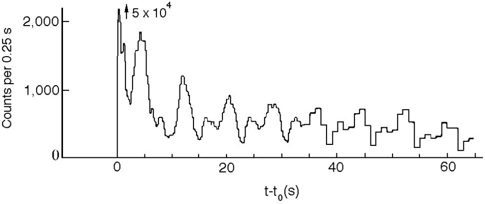
Numerical simulations show that 10^{18} G could even be reached.

Huge amount of magnetic energy can be occasionally released in **crustquakes** producing γ-ray bursts.



The March 5, 1979 event

The theory of magnetars was proposed in 1992 by Robert Duncan, Christopher Thompson and Bohdan Paczynski to explain **Soft-Gamma Repeaters** (SGR). SGRs are repeated sources of x- and γ-ray bursts. The first such object called SGR 0525$-$66 was discovered in 1979.

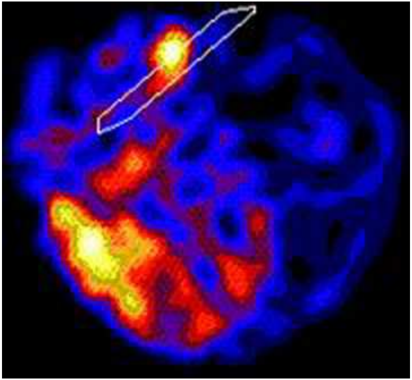


A very **intense gamma-ray burst** was detected on March 5, 1979 by two Soviet satellites Venera 11 and Venera 12.

The burst lasted about 3 minutes and showed a periodic modulation of 8 seconds.

Mazets et al., Nature 282 (1979), 587.

The March 5, 1979 event



ROSAT

The source was later found to lie inside a supernova remnant in the Large Magellanic Cloud (N49) thus suggesting that it might be a young isolated neutron star. But it was difficult at that time to explain the origin of the bursts.

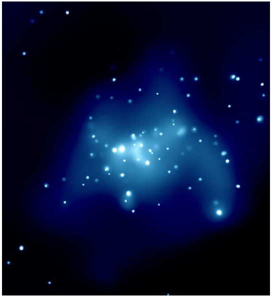
Other burst sources have been found. 14 SGRs (11 confirmed, 3 candidates) are currently known (June 2015).

`http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

Anomalous X-ray pulsars

Anomalous X-ray pulsars (AXP) are isolated sources of pulsed x-rays. Their periods range from 2 to 12 s and their spin-down rate $\dot{P} \sim 10^{-11}$ so that $B \sim 10^{14}$ G. Some of them are bursters.

SGR and AXP have much in common. **Their observed x-ray luminosity is much larger than their kinetic energy loss rate** suggesting these objects are powered by magnetic field decay. SGR and AXP are thought to belong to the same class of neutron stars: magnetars.



CXO J164710.2-455216 (Chandra)

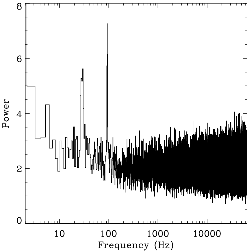
14 AXPs (12 confirmed, 2 candidates) are known (June 2015).

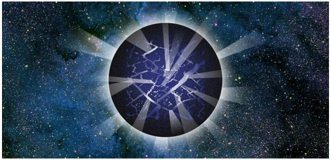
`http://www.physics.mcgill.ca/~pulsar/magnetar/main.html`

Magnetar seismology

Quasi Periodic Oscillations (QPO) have been discovered in the x-ray flux of giant flares from SGR 1806−20, SGR 1900+14 and SGR 0526−66.

Watts & Strohmayer, Adv. Space Res. 40, 1446 (2007).





These QPOs coincide reasonably well with **seismic crustal modes thought to arise from the release of magnetic stresses**.

Thompson & Duncan, MNRAS 275, 255 (1995)

The **huge luminosity variation** suggests $B \gtrsim 10^{15}$ G at the star surface thus lending support to the magnetar scenario.

Vietri et al., ApJ 661, 1089 (2007).

Cyclotron lines in SGR and AXP

Evidence for proton cyclotron lines have been found in the spectra of a few SGR and AXP during bursts:

	B_{spec} (in G)	B_{spin} (in G)
SGR 1900+14	2.6×10^{15}	7×10^{14}
SGR 1806−20	$\sim 10^{15}$	2×10^{14}
1E 1048−59	2.1×10^{15}	4.2×10^{14}
XTE J1810−197	2×10^{15}	2.1×10^{14}
4U 0142+61	4.75×10^{14}	1.3×10^{14}

Mereghetti, Astron. Astrophys. Rev. 15, 225 (2008).

The magnetic fields inferred from both spin-down and spectroscopic studies (not only cyclotron lines but also continuum) are consistent with the magnetar scenario:

$$B > \frac{m_e^2 c^3}{e\hbar} \simeq 4.4 \times 10^{13} \text{ G}$$

Microscopic model of magnetar crusts

Main assumptions:

- the crust is a solid crystal made of only one type of ions ${}^A_Z X$

  $$T < T_m \approx 1.3 \times 10^5 Z^2 \left(\frac{\rho_6}{A}\right)^{1/3} \text{ K} \qquad \rho_6 \equiv \rho/10^6 \text{ g cm}^{-3}$$

- electrons are uniformly distributed and are highly degenerate

  $$T \ll T_{\rm F} \approx 4.1 \times 10^9 \frac{Z}{A} \frac{\rho_6}{B_\star} \text{ K}$$

- matter is fully catalyzed.

The only microscopic inputs are nuclear masses. We have made use of the experimental data (Atomic Mass Evaluation) complemented with microscopic mass models based on the nuclear energy density functional theory.

Chamel et al.,Phys.Rev.C86, 055804(2012).

Nuclear energy density functional theory

The energy $E\left[n_q(\boldsymbol{r}), \nabla n_q(\boldsymbol{r}), \tau_q(\boldsymbol{r}), \boldsymbol{J_q}(\boldsymbol{r})\right]$ can be expressed as a *functional* of various densities and currents ($q = n, p$):

$$n_q(\boldsymbol{r}) = \sum_{k,\sigma=\uparrow,\downarrow} |\varphi^{(q)}_{k\sigma}(\boldsymbol{r})|^2, \qquad \tau_q(\boldsymbol{r}) = \sum_{k,\sigma=\uparrow,\downarrow} |\boldsymbol{\nabla}\varphi^{(q)}_{k\sigma}(\boldsymbol{r})|^2$$

$$\boldsymbol{J_q}(\boldsymbol{r}) = \frac{\mathrm{i}}{2} \sum_{k,\sigma,\sigma'=\uparrow,\downarrow} \left\{ \varphi^{(q)}_{k\sigma}(\boldsymbol{r}) \boldsymbol{\nabla}\varphi^{(q)}_{k\sigma'}(\boldsymbol{r})^* - \varphi^{(q)}_{k\sigma'}(\boldsymbol{r})^* \boldsymbol{\nabla}\varphi^{(q)}_{k\sigma}(\boldsymbol{r}) \right\} \times \langle\sigma'|\hat{\boldsymbol{\sigma}}|\sigma\rangle$$

The single-particle wavefunctions $\varphi^{(q)}_{k\sigma}(\boldsymbol{r})$ are obtained from the *self-consistent* “Hartree-Fock” (HF) equations:

$$\left[-\boldsymbol{\nabla}\cdot\frac{\hbar^2}{2M^\star_q(\boldsymbol{r})}\boldsymbol{\nabla} + U_q(\boldsymbol{r}) - \mathrm{i}\boldsymbol{W_q}(\boldsymbol{r})\cdot\boldsymbol{\nabla}\times\boldsymbol{\sigma}\right]\varphi^{(q)}(\boldsymbol{r}) = \varepsilon^{(q)}\varphi^{(q)}(\boldsymbol{r})$$

$$\frac{\hbar^2}{2M^\star_q(\boldsymbol{r})} \equiv \frac{\delta E}{\delta\tau_q(\boldsymbol{r})}, \qquad U_q(\boldsymbol{r}) \equiv \frac{\delta E}{\delta n_q(\boldsymbol{r})}, \qquad \boldsymbol{W_q}(\boldsymbol{r}) \equiv \frac{\delta E}{\delta \boldsymbol{J_q}(\boldsymbol{r})}.$$

This scheme can be extended to account for nuclear pairing: Hartree-Fock-Bogoliubov (HFB) equations.

Problem: we don’t know what the exact functional is... We have thus to rely on phenomenological functionals.

Which functional should we choose?

The nuclear energy density functional theory has been very successfully applied to describe the structure and the dynamics of medium-mass and heavy nuclei.

However, most functionals are not suitable for astrophysical applications:

- they were adjusted to a few selected nuclei (mostly in the stability valley)
- they yield unrealistic neutron-matter equation of state
- they yield unrealistic pairing gaps in nuclear matter
- they yield unrealistic effective masses
- they lead to spurious instabilities in nuclear matter (e.g. ferromagnetic transition).

Brussels-Montreal Skyrme functionals (BSk)

These functionals were fitted to both experimental data and N-body calculations using realistic forces.

Experimental data:

- all atomic masses with $Z, N \geq 8$ from the Atomic Mass Evaluation (root-mean square deviation: 0.5-0.6 MeV)

  `http://www.astro.ulb.ac.be/bruslib/`
- charge radii
- incompressibility $K_v = 240 \pm 10$ MeV (ISGMR)
  Colò et al., Phys.Rev.C70, 024307 (2004).

N-body calculations using realistic forces:

- equation of state of pure neutron matter
- $^1S_0$ pairing gaps in nuclear matter
- effective masses in nuclear matter

Phenomenological corrections for atomic nuclei

For atomic nuclei, we add the following corrections:

- Wigner energy

$$E_W = V_W \exp\left\{ -\lambda \left(\frac{N-Z}{A} \right)^2 \right\} + V'_W |N-Z| \exp\left\{ -\left(\frac{A}{A_0} \right)^2 \right\}$$

  $V_W \sim -2$ MeV, $V'_W \sim 1$ MeV, $\lambda \sim 300$ MeV, $A_0 \sim 20$

- rotational and vibrational spurious collective energy

$$E_{\rm coll} = E_{\rm rot}^{\rm crank} \Big\{ b \ \tanh(c|\beta_2|) + d|\beta_2| \ \exp\{-l(|\beta_2| - \beta_2^0)^2\} \Big\}$$

This latter correction was shown to be in good agreement with more elaborate calculations (5D collective Hamiltonian).
Goriely, Chamel, Pearson, Phys.Rev.C82,035804(2010).

In this way, these collective effects do not contaminate the parameters (≤ 20) of the functional.

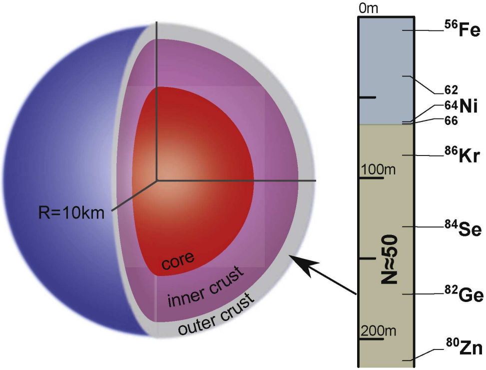
Brussels-Montreal Skyrme functionals

Main features of the latest functionals:

- **fit to realistic $^1S_0$ pairing gaps** in symmetric and neutron matter (BSk16-17)
  Chamel, Goriely, Pearson, Nucl.Phys.A812,72 (2008)
  Goriely, Chamel, Pearson, PRL102,152503 (2009).
- **removal of spurious spin and spin-isospin instabilities** in nuclear matter (BSk18)
  Chamel, Goriely, Pearson, Phys.Rev.C80,065804(2009)
- **fit to realistic neutron-matter equation of state** (BSk19-21)
  Goriely, Chamel, Pearson, Phys.Rev.C82,035804(2010)
- **fit to different symmetry energies** (BSk22-26)
  Goriely, Chamel, Pearson, Phys.Rev.C88,024308(2013)
- **optimal fit of the 2012 AME** - rms 0.512 MeV (BSk27*)
  Goriely, Chamel, Pearson, Phys.Rev.C88,061302(R)(2013)
- **generalized spin-orbit coupling** (BSk28-29)
  Goriely, Nucl.Phys.A933,68(2015).

Composition of the outer crust of a neutron star

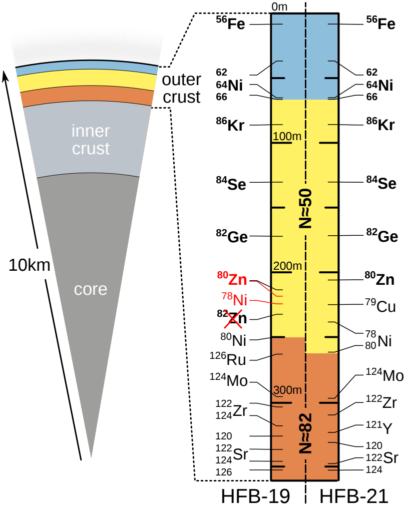
The composition of the crust is completely determined by experimental nuclear masses down to about 200m for a 1.4$M_\odot$ neutron star with a 10 km radius



Roca-Maza, Piekarewicz, Phys.Rev.C78,025807(2008)
Pearson,Goriely,Chamel,Phys.Rev.C83,065810(2011)
Kreim, Hempel, Lunney, Schaffner-Bielich, Int.J.M.Spec.349-350,63(2013)

Plumbing neutron stars to new depths

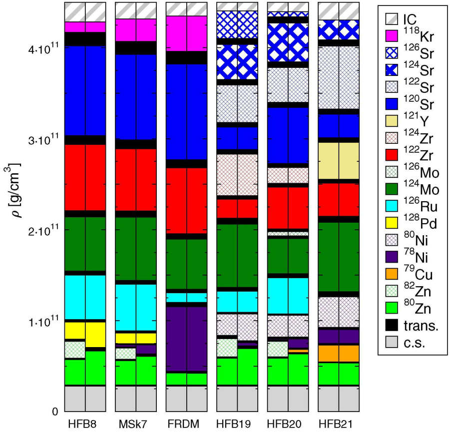
New precision measurements of the mass of short-lived zinc nuclides by the ISOLTRAP collaboration at CERN's ISOLDE radioactive-beam facility has recently allowed to "drill" deeper into the crust.



Wolf et al.,PRL110,041101(2013).

Composition of the outer crust of a nonaccreting neutron star (catalyzed matter)

Deeper in the star, the composition is model-dependent:



Kreim, Hempel, Lunney, Schaffner-Bielich, Int.J.M.Spec.349-350,63(2013)

Impact of a strong magnetic field on the composition

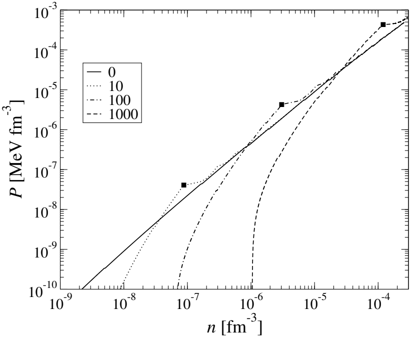
Sequence of nuclides for HFB-21 and $B_\star \equiv B/(4.4 \times 10^{13}$ G):

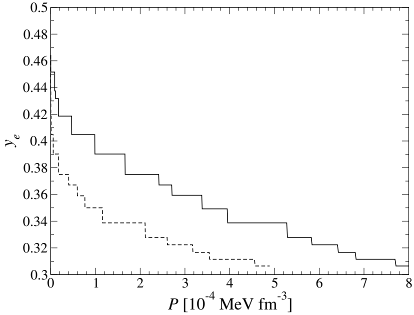
$B_\star = 0$	$B_\star = 1$	$B_\star = 10$	$B_\star = 100$	$B_\star = 1000$	$B_\star = 2000$
^{56}**Fe**	^{56}**Fe**	^{56}**Fe**	^{56}**Fe**	^{56}**Fe**	^{56}**Fe**
^{62}**Ni**	^{62}**Ni**	^{62}**Ni**	^{62}**Ni**	^{62}**Ni**	^{62}**Ni**
^{58}**Fe**	^{58}**Fe**	–	–	–	–
^{64}**Ni**	^{64}**Ni**	^{64}**Ni**	^{64}**Ni**	^{64}**Ni**	–
^{66}**Ni**	^{66}**Ni**	^{66}**Ni**	–	–	–
–	–	–	–	^{88}**Sr**	^{88}**Sr**
^{86}**Kr**	^{86}**Kr**	^{86}**Kr**	^{86}**Kr**	^{86}**Kr**	^{86}**Kr**
^{84}**Se**	^{84}**Se**	^{84}**Se**	^{84}**Se**	^{84}**Se**	^{84}**Se**
^{82}**Ge**	^{82}**Ge**	^{82}**Ge**	^{82}**Ge**	^{82}**Ge**	^{82}**Ge**
–	–	–	–	–	^{132}**Sn**
^{80}**Zn**	^{80}**Zn**	^{80}**Zn**	^{80}**Zn**	^{80}**Zn**	^{80}**Zn**
–	–	–	–	–	^{130}**Cd**
–	–	–	–	–	^{128}Pd
–	–	–	–	–	^{126}Ru
^{79}Cu	^{79}Cu	^{79}Cu	^{79}Cu	^{79}Cu	–
^{78}Ni	^{78}Ni	^{78}Ni	^{78}Ni	^{78}Ni	–
^{80}Ni	^{80}Ni	^{80}Ni	^{80}Ni	^{80}Ni	–
^{124}Mo	^{124}Mo	^{124}Mo	^{124}Mo	^{124}Mo	^{124}Mo
^{122}Zr	^{122}Zr	^{122}Zr	^{122}Zr	^{122}Zr	^{122}Zr
^{121}Y	^{121}Y	^{121}Y	^{121}Y	^{121}Y	^{121}Y
^{120}Sr	^{120}Sr	^{120}Sr	^{120}Sr	^{120}Sr	^{120}Sr
^{122}Sr	^{122}Sr	^{122}Sr	^{122}Sr	^{122}Sr	^{122}Sr
^{124}Sr	^{124}Sr	^{124}Sr	^{124}Sr	^{124}Sr	^{124}Sr

Chamel et al.,Phys.Rev.C86, 055804(2012).

Equation of state of the outer crust of magnetars

Matter in a magnetar is much more incompressible and less neutron-rich than in a neutron star.





$$P \approx P_0 \left(\frac{n}{n_s} - 1 \right)^2$$

$$y_e \approx \frac{1}{2} \left(1 - \sqrt{\frac{\pi^2 \lambda_e^3 m_e c^2 P}{4 B_\star J^2}} \right)$$

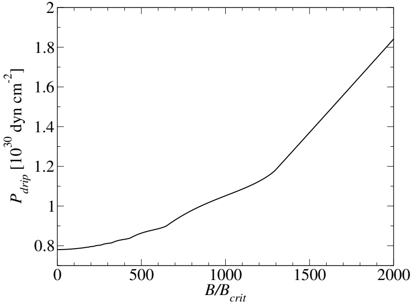
Chamel et al.,Phys.Rev.C86, 055804(2012).

Neutron drip transition in magnetars

With increasing density, nuclei become progressively more neutron rich. At some point, neutrons start to drip out.

In the strongly quantizing regime, $\mu_e^{\rm drip} = \dfrac{-M(A,Z)c^2 + Am_nc^2}{Z}$

$$P_{\rm drip} \approx \frac{B_\star \mu_e^{\rm drip\,2}}{4\pi^2\lambda_e^3 m_e c^2}\left[1 - \frac{1}{3}C\alpha Z^{2/3}\left(\frac{4B_\star}{\pi^2}\right)^{1/3}\left(\frac{m_e c^2}{\mu_e^{\rm drip}}\right)^{2/3}\right]$$



Example using HFB-24 and $C = -1.44423$ (bcc lattice).

We find that the dripping nucleus is $^{124}_{38}$Sr independently of B.

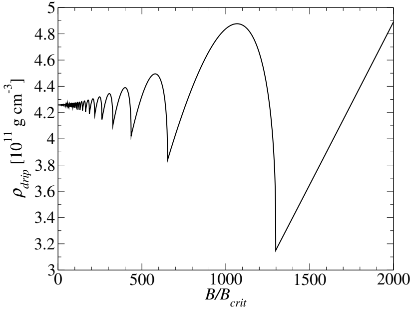
$\mu_e^{\rm drip} \approx 24.81$ MeV.

Chamel et al.,Phys.Rev.C91, 065801(2015).

Neutron drip transition in magnetars

The neutron drip density exhibits typical quantum oscillations.

Example using HFB-24:



These oscillations are almost universal:

$$\frac{\rho_{\rm drip}^{\rm min}}{\rho_{\rm drip}(B_\star = 0)} \approx \frac{3}{4}$$

$$\frac{\rho_{\rm drip}^{\rm max}}{\rho_{\rm drip}(B_\star = 0)} \approx \frac{35 + 13\sqrt{13}}{72}$$

In the strongly quantizing regime,

$$\rho_{\rm drip} \approx \frac{A}{Z} m \frac{\mu_e^{\rm drip}}{m_e c^2} \frac{B_\star}{2\pi^2 \lambda_e^3} \left[1 - \frac{4}{3} C\alpha Z^{2/3} \left(\frac{B_\star}{2\pi^2} \right)^{1/3} \left(\frac{m_e c^2}{\mu_e^{\rm drip}} \right)^{2/3} \right]$$

Chamel et al.,Phys.Rev.C91, 065801(2015).

Conclusions & Perspectives

Electron captures by nuclei and neutron emissions play a crucial role in dense astrophysical environments.

- The ultramagnetic white dwarf models of Das&Mukhopadhay for the progenitors of overluminous SNIa are found to be highly unstable against electron captures.
- The crust of a neutron star contains very exotic nuclei due to electron captures. Deep enough, nuclei emit neutrons. The composition can change in a strong magnetic field.

(Some) perspectives:

- White and strange dwarfs may still have strong *non-uniform* magnetic fields. Calculations in full GR are in progress.
- A strong magnetic field can affect nuclei. Nuclear mass models should thus be extended.