Exotic atoms at extremely high magnetic fields: the case of Neutron Stars atmosphere

Wien, 12.09.2017

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[6]National Superconducting Cyclotron Laboratory, Michigan State University and Theoretical Division, Los Alamos National Laboratory

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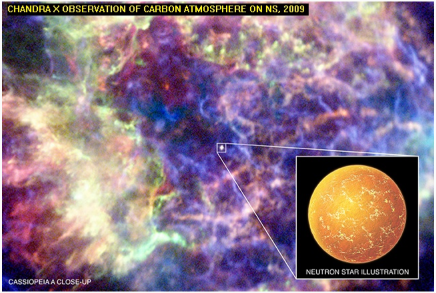

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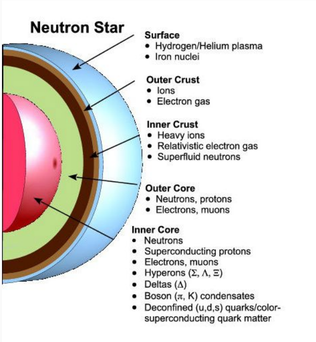
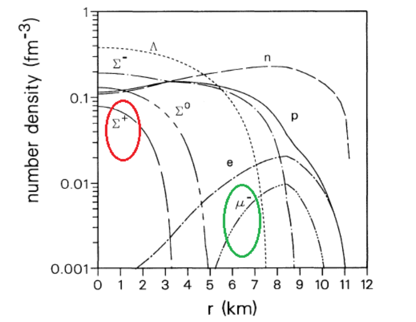
- Key facts about Neutron Stars
  Mass and radius
  Star composition
  Magnetic field
- Exotic atoms on NS?
  Quark/Hybrid stars
  NS/QS conversion
- Atoms in extreme magnetic fields
  Cylindrical atoms
  Center of mass motion
  Hydrogen spectrum
  Muonic hydrogen/Sigmium
- Outlook

NEUTRON STAR





Not only neutrons!

Main features of a Neutron Star (NS)[1,2]:

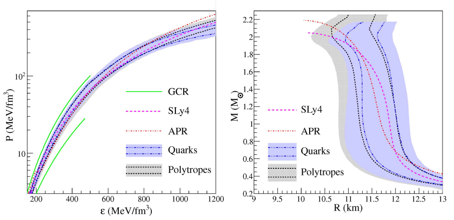
- very high density: nuclear saturation: $\rho_{sat} \approx 2.5 \times 10^{14} \frac{g}{cm^3}$ - NS surface: $\approx 3 \times 10^{-3} \rho_{sat}$ - NS core: $\approx 7 \times \rho_{sat}$
- extremely intense magnetic field: ms pulsar: $10^7\ G$ - magnetar: $10^{16}\ G$
- ...

EQUATION OF STATE

Key goal: to determine the **equation of state** (EOS) for ultradense matter, i.e. the relation between density and pressure:

- At densities exceeding a few times the nuclear density, exotic states of matter may appear such as **hyperons** and Bose condensates
- At higher densities a phase transition to **strange quark matter** may occur

Ultradense matter EOS manifests itself as a **mass-radius** (M-R) relation.



GCR: quantum Monte Carlo calculations

SLy4: Skyrme density functional calculation

APR: variational calculations

Many theoretical EOS available in the literature, each predicting a different M-R relation for NS.

MASS AND RADIUS

Mass and **radius** are the **main observables** in the study of NS:

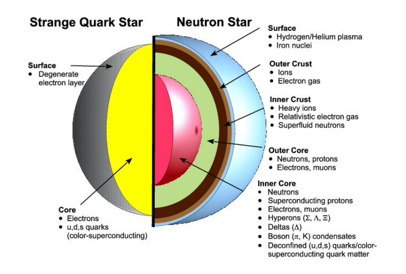
- Masses are measured with great precision from binary radio pulsars timing
- Radius measurements much more challenging, no reliable data
- M and R simultaneous methods not available

$\rightarrow$ difficult to discriminate between EOS models.

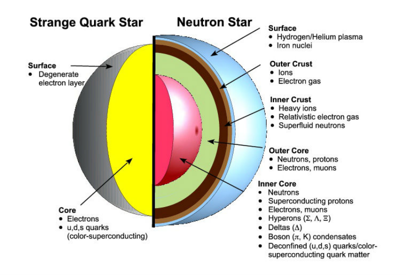
Some **open** *classical* **problems**:

- Stiffness of the equation of state
- **Hyperon puzzle** (hyperons soften the EOS and reduce mass)
- Importance of three-body interactions and role of delta resonances
- The very **nature of star** uncertain: Neutron, Quark or Hybrid stars?

NEUTRON STAR/QUARK STAR



NEUTRON STAR/QUARK STAR



The **conversion process** of a NS into a QS was proposed by different authors [8,9] and is still under study.

Two Families scenario [10,11]:

droplet becomes a macroscopic expanding bubble of QM. **Hydrodynamical** description in two steps: rapid burning (few ms), favoured by instabilities, followed by slow burning ($\sim$10 s), with strangeness diffusion.

In this model NS co-exist with **quark stars** (QS):

- NS can be very compact and have a maximum mass of $\sim 1.5 - 1.6 M_{\odot}$
- QS can have large radii and be even more massive, up to $2.75 M_{\odot}$.

NS/QS CONVERSION AND TWO FAMILIES SCENARIO

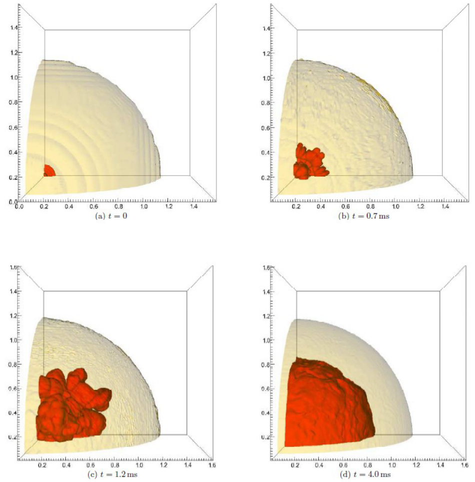
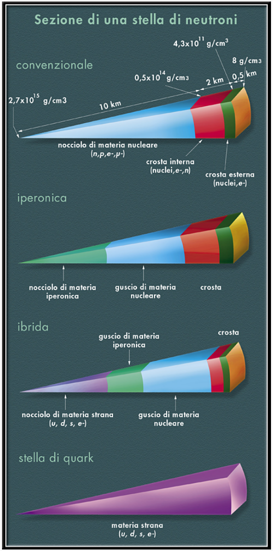


FIG. 1: (color online) Model: Set 1, $M = 1.4 M_\odot$. Conversion front (red) and surface of the neutron star (yellow) at different times t. Spatial units 10^6 cm.

- Three-dimensional **hydrodynamic simulations** of the combustion process: temperature profiles and expected neutrino signal.
- The process is a powerful source of neutrinos: initial luminosity $3 \times 10^{52} erg/s$.
- Neutrino ablation can lead to a **significant mass ejection** of the nuclear envelope.

MODELS FOR NS/QS CONVERSION



Other models:

- Quark **Droplet Nucleation**: [12]

  quark deconfinement as first order phase transition, with formation of a critical size drop (as dew formation in supersaturated vapor).

- **Quark-Novae** model [13]

  quark deconfinement as detonation/deflagration, with significant amount of matter ejection by a mechanical shock at the end of the process.

In all cases, **exotic matter** could be **ablated by neutrinos** towards the surface of the star.

ATMOSPHERE OF NS

We focus our attention on the **atmosphere**:

- theoretical models from H, He, C atmospheres and for Fe crust
- difference between isolated and binary NS (accretion process)
- good fits to data by recent C atmosphere models

Given the uncertainties on the EOS for these stars, it is worth to look for **new observables**:

1. looking first at the H case...
2. ...and trying to extend what we find to exotic atoms.

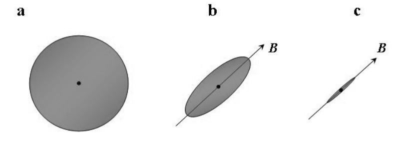
The **atmosphere of a QS** could be radically **different** from the **atmosphere of a NS**. Is there a chance to distinguish between these two types of compact stars?

Effects of a **strong magnetic field** on H atoms (grey areas: ellipsoids with probability to find an electron $> e^{-1}$; solid dots: protons)

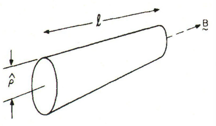
a) $B \ll 10^9 G$

b) $B = 10^9 G$

c) $B = 10^{12} G$



E field as perturbation: "spherical" atomic levels $\rightarrow$ **"cylindrical" atomic levels** [3,4]



$$\hat{\rho} = \rho_0 \ll a_0$$

ρ_0 : radius of ground state

Reference field for NS: $B_0 = \frac{m_e^2 e^3 c}{\hbar^3} = 2.3505 \times 10^9 G$, corresponding to cyclotron radius $\equiv$ Bohr radius.

QUANTUM MECHANICAL TREATMENT

- Numerical **solutions** exist **only for H** atom
- Landau energy levels: principal quantum number n
- 1D Schrödinger equation with solution $f_{m\nu}(z)$:

$$-\frac{\hbar^2}{2m_e\rho_0^2}f''_{m\nu} - \frac{e}{\rho_0}V_m(z)f_{m\nu} = E_{m\nu}f_{m\nu} \qquad m,\nu = 0,1,2,\ldots$$

- **Two quantum numbers** m and ν: m for radial excitations

$$\rho_m = (2m+1)^{1/2}\rho_0 \qquad m = 0,1,2,\ldots$$

  and ν to account for longitudinal nodes
- **Two types of states**[5]:

DEEPLY BOUND	WEAKLY BOUND
$m \geq 0 \quad \nu = 0$	$m \geq 0 \quad \nu > 0$

Classification of states with the parameter $b \equiv \frac{B}{B_0}$

ENERGY LEVELS

INFINITE PROTON MASS

$$E_{m0} \approx -0.16 l_m^2 \quad \text{a.u.} \quad (\text{for } 2m+1 \ll b) \quad l_m = \ln\left(\frac{b}{2m+1}\right)$$

$$E_{m\nu} = -\frac{1}{(2\nu_1 + \delta)^2} \quad \text{a.u.} \qquad (\nu_1 = 1, 2, 3, \dots)$$

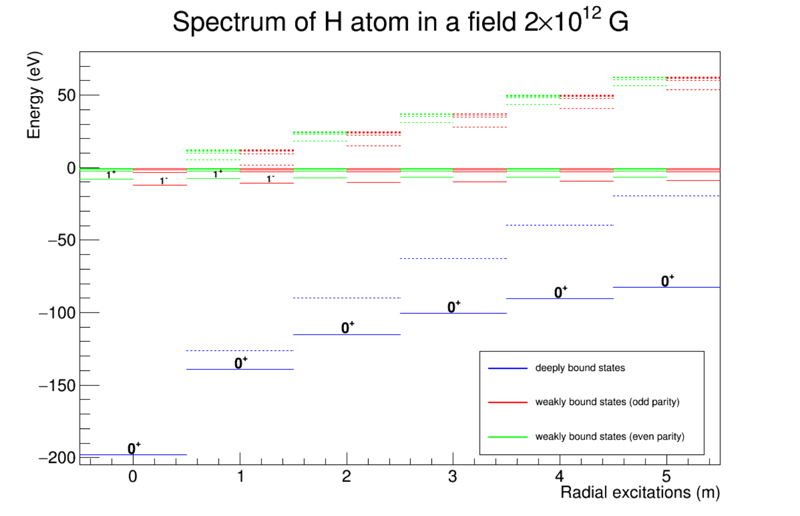
$$\delta = \begin{cases} 2\rho_m / a_0 & \nu = 2\nu_1 - 1 \\ [\ln(a_0/\rho_m)]^{-1} & \nu = 2\nu_1 \end{cases}$$

FINITE PROTON MASS

$$m_e \to \mu = \frac{m_e \times m_p}{m_e + m_p}$$

$$\Delta E = 29.6\, m \, \frac{B}{4.7 \times 10^{12}\, G} \, eV$$

ENERGY LEVELS



Continuous lines: infinite proton mass

Dashed lines: finite proton mass

CENTER OF MASS MOTION

Atoms motion described by a **pseudo-momentum K**, derived from canonical momentum Π [6]:

$$\boldsymbol{K} \equiv \Pi - \frac{e}{c}\boldsymbol{B} \times \boldsymbol{r}$$

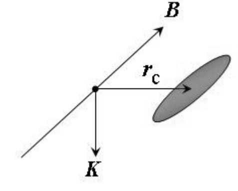
$$\boldsymbol{K} = \boldsymbol{K}_e + \boldsymbol{K}_p,$$

$$\boldsymbol{r}_c = \frac{c\boldsymbol{B} \times \boldsymbol{K}_\perp}{eB^2}, \qquad r_c = \frac{K_\perp}{b} \text{ a.u.}$$

$K_\perp$: $\boldsymbol{K}$ component orthogonal to $\boldsymbol{B}$.

Motion unit scale:

$$1\, K_\perp(a.u.) = 3.73\, keV/c$$



Two different solutions:

- centered states
- **decentered** states

Atoms moving across **B** may become decentered: **proton external to electron cloud!**

The guiding center $\mathbf{r}_c$ is perpendicular to **B** and to **K**.

SOLUTION FOR HYDROGEN

Deeply bound states

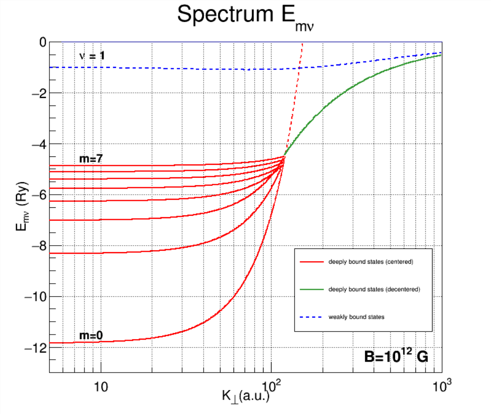
- centered states:

$$E_{m0}(K_\perp) \simeq E_m + \frac{K_\perp^2}{2M_{\perp\,m}}$$

$M_{\perp\,m}$: effective transverse mass

- decentered states:

$$E_{m0}(K_\perp) \sim -\frac{b}{K_\perp}$$



Weakly bound states:
analytical approximations[7]

Validity limit of the model: $100 \leq b \leq 10^6$.

EXOTIC ATOMS?

VALIDITY LIMIT

$$100 \leq b \leq 10^6$$

DEFINITION

$$b = \frac{B}{B_0} = \frac{\hbar^3 B}{m_e^2 e^3 c}$$

EXOTIC ATOMS?

DEFINITION

$$b = \frac{B}{B_0} = \frac{\hbar^3 B}{m_e^2 e^3 c}$$

VALIDITY LIMIT

$$100 \leq b \leq 10^6$$

- **muonic hydrogen** (p-μ^-):

$$m_e \to m_\mu \quad \to \quad b = \frac{\hbar^3 B}{m_\mu^2 e^3 c}, \frac{b}{b^H} \sim 10^{-2} \to B : 10^{12}\ G \to 10^{16}\ G$$

EXOTIC ATOMS?

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- **Sigmium** ($\Sigma^+ - e^-$):

$$m_e \to m_\Sigma \quad \to \quad b = \frac{\hbar^3 B}{m_\Sigma^2 e^3 c}, \frac{b}{b^H} \sim 1 \to B : 10^{12}\ G \to 10^{12}\ G$$

EXOTIC ATOMS?

VALIDITY LIMIT

$$100 \leq b \leq 10^6$$

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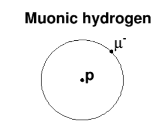
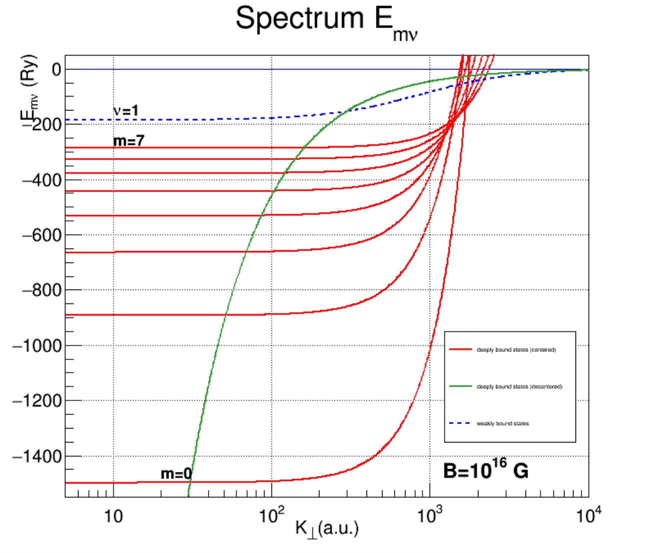
Scaling rule:

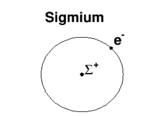
$$z = \frac{\mu}{m_e}, \qquad a_0 = \frac{a_0^H}{z} \qquad E = z \times E^H$$

MUONIC HYDROGEN

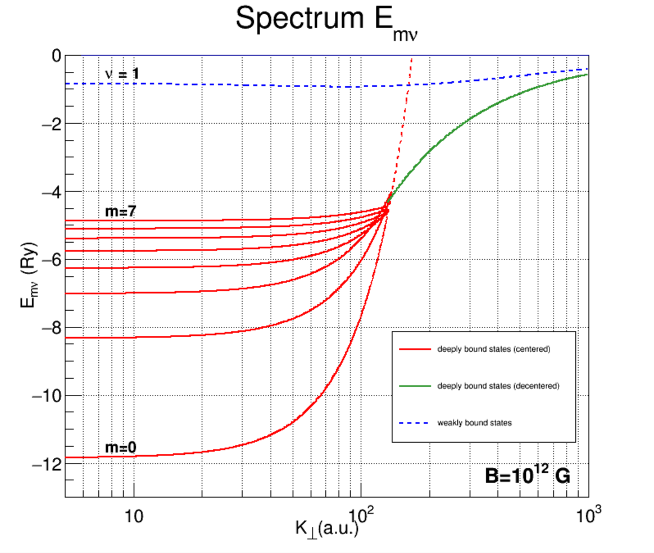




SIGMIUM



Sigmium
e-
Σ+



Spectrum E_mν
ν = 1
m=7
m=0
E_mν (Ry)
K⊥(a.u.)
0
−2
−4
−6
−8
−10
−12
10
10^2
10^3
deeply bound states (centered)
deeply bound states (decentered)
weakly bound states
B=10^12 G

PRELIMINARY RESULTS FOR $1^- \to 0^+$

Atom	$K_\perp$ (a.u.)	Energy (eV)	λ (nm)	Note
Hydrogen	0	147.5877	8.4	**UV**
"	10	146.6178	8.5	"
"	50	129.1634	9.6	"
"	100	77.6384	16	"
Muonic hydrogen	0	17848.5	0.06946	**X-ray**
"	10	17851.5	0.069453	"
"	50	17870.2	0.069381	"
"	100	17885.1	0.069323	"
Sigmium	0	149.832	8.27	**UV**
"	10	149.029	8.32	"
"	50	134.488	9.22	"
"	100	91.7076	13.52	"

Transitions with B intensities as indicated in the previous slides.

CONCLUSIONS

- Hydrogen-like atoms, involving μ^-, Σ^+ or other **exotic constituents** could be formed in the NS/QS conversion
- We have investigated the **energy levels structure** of hypothetical exotic atoms and made some predictions on transitions that could help to **discriminate among EOS**
- Hyperfine interaction for cylindrical atoms: calculation in progress. . .
- If the results are confirmed, the proposed calculations could give a **direct evidence** of the presence of **hyperons on NS**
- **Request** to the community: it would be interesting to
    1. Estimate **radial exotic fractions** during conversion process
    2. **Numerically solve** 1D Schrödinger equation for exotic atoms

ACKNOWLEDGMENTS

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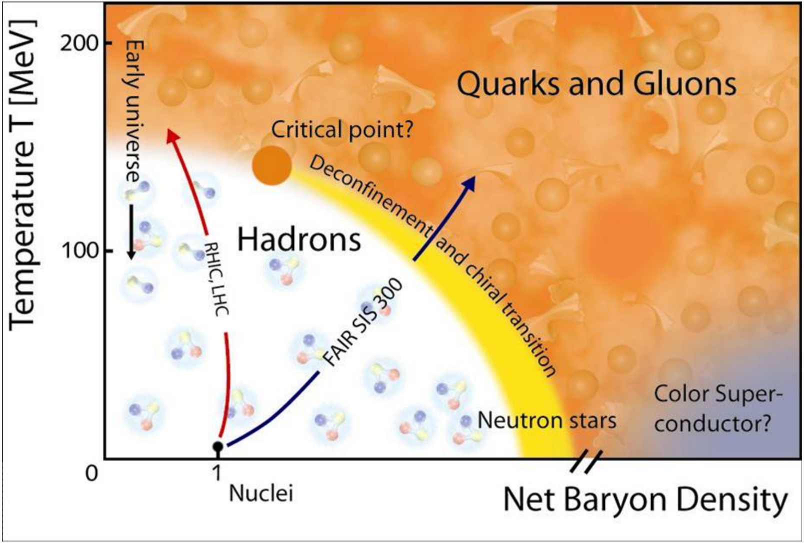
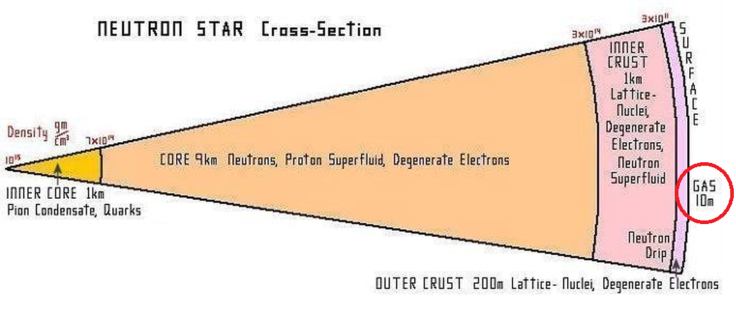
Backup slides

QUARK GLUON PLASMA



NEUTRON STARS

Original star mass (in $M_\odot$)	Process	Final object
$1 < M < 8$	Planetary Nebula	White Dwarf
$\sim 8 - 10$	Supernova	**Neutron Star**
> 10	Supernova	Black Hole



- Degenerate Fermi gas $\rightarrow$ $R \sim 10\,km$ e $M \sim 1.5 M_\odot$
- **Giant nucleus** ($A_c \simeq 0.11 \times 10^{57}$ $A_{NS} \sim 1.6 \times 10^{57}$)

MASSES

Classification by the **maximum mass** M_{max} that the EOS can sustain:

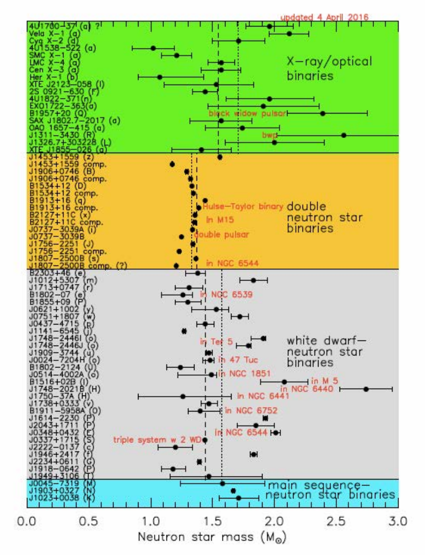
- **Soft EOS** (low central density) $\rightarrow$ $M_{max} \sim 1.5 - 1.7 M_{\odot}$
- **Stiff EOS** (high central density) $\rightarrow$ $M_{max} \sim 2.4 - 2.5 M_{\odot}$

Recent observations:

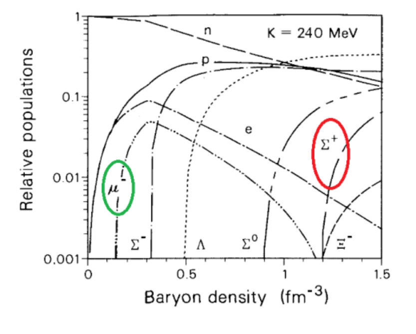
PSR J1614-2230: $M = 1.97 \pm 0.04 M_{\odot}$

PSR J0348-0432: $M = 2.01 \pm 0.04 M_{\odot}$

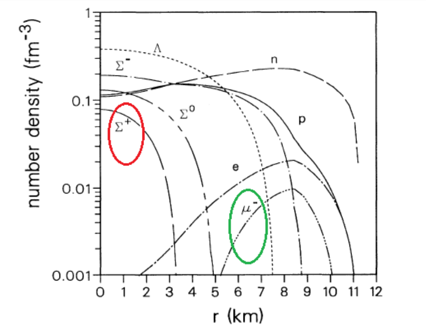
seem to **rule out** most **soft EOS** and to limit the presence of quark matter in the NS core.



Not only neutrons!



Distribution of particles vs density of matter



Distribution of particles vs radius

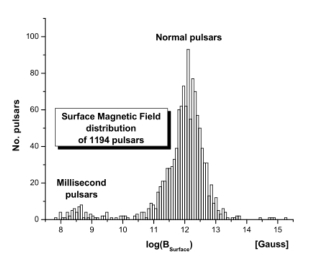
Nuclear interactions (NN,YN,YY,NNN,NNY,NYY&YYY) are crucial and well studied in the core [1,2].

Any **EM interaction** among these particles?

NEUTRON STAR MAGNETIC FIELD

Typical fields on NS

Type of pulsar	Surface magnetic field
Millisecond	$10^7 - 10^9\,G$
Normal	$10^{12}\,G$
Magnetar	$10^{14} - 10^{16}\,G$

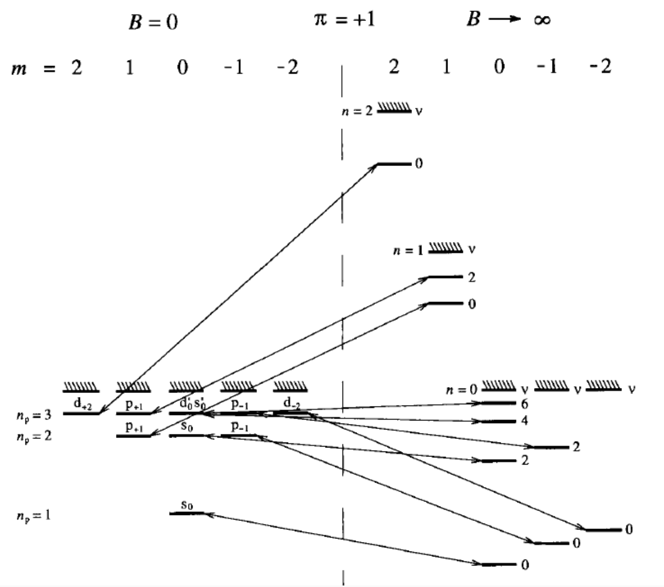


Origin:

- Conservation of magnetic flux during gravitational collapse of iron core
- Electric currents flowing in the highly conductive NS interior
- Spontaneous transition to a ferromagnetic state due to nuclear interactions

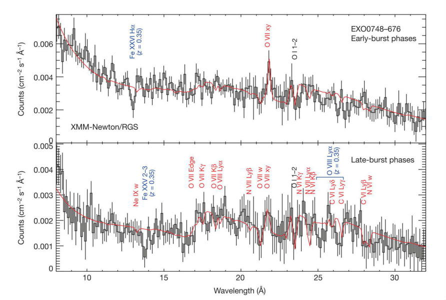
Extremely high compared to other natural or laboratory fields (pulsed max in lab $\sim 2.8 \times 10^7\,G$).

ENERGY LEVELS CORRESPONDENCE

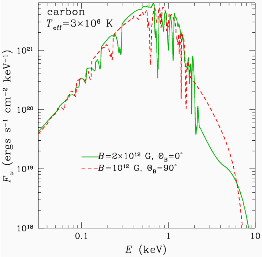


POSSIBLE FUTURE STUDIES

- **Search** of these lines in available datasets



EXO07482676 spectrum from XMM-Newton



CAS A C spectrum from Chandra X

- Estimate **radial exotic fractions** during conversion process (taking possibly into account also particles lifetimes)
- **Numerically solve** Schrödinger equation for exotic atoms
- Hyperfine interaction for cylindrical atoms
- Recent new missions as NICER, LOFT as source of new data

HYPERFINE SPLITTING

Evaluation of the **hyperfine constant** for cylindrical atoms:

$$a_J = 2\,\mu_B \gamma_I \hbar \frac{l(l+1)}{j(j+1)} < r^{-3} >_{l\neq 0}$$

Expectation value of $< r^{-3} >$ on the 1D states.

- Traditional atoms:

$$< r^{-3} > = \frac{1}{l(l+1)(l+\frac{1}{2})} \left(\frac{Z}{n\,a_0}\right)^3$$

- **Cylindrical atoms** (tightly bound states):

$$< r^{-3} > = \left[\frac{\sqrt{\lambda_m^2}\gamma^m}{\Gamma(m+1)} I_1\, I_2\right] \frac{2}{\sqrt{\pi}} \left(\frac{b}{2}\right)^{3/2} \left(\frac{Z}{a_0}\right)^3$$

with λ_m obtained with variational methods, $\gamma = \frac{1}{2\rho_0^2}$, I_1 and I_2 integrals on the radial and longitudinal part of the wavefunction.

In principle, each level becomes a **doublet**.