Nuclei of greatest impact on the composition of neutron-star outer crusts

Irene Dedes Nonell

Advisor: Mario Centelles

Department of Structure and Constituents of Matter

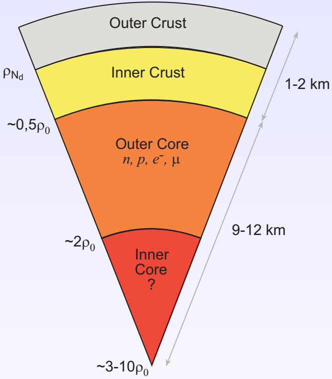
Faculty of Physics, University of Barcelona, SPAIN

November 19, 2014

What Are Neutron Stars?

- Remnants of supernovae explosions
- ‘Small’: Typical radius of 10 km and mass of $1.5 - 2$ solar masses
- Some of the densest objects in the universe
- They appear as ‘natural laboratories’ to test the physical theories of nuclear dense matter

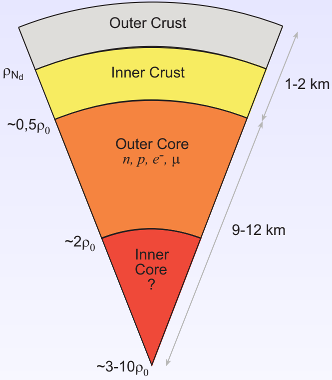
Structure of a Neutron Star



- The core is composed of uniform nuclear matter under the β-stability and the charge neutrality conditions:

The composition: $(n,\ p,\ e^-,\ \mu^-)$

Structure of a Neutron Star

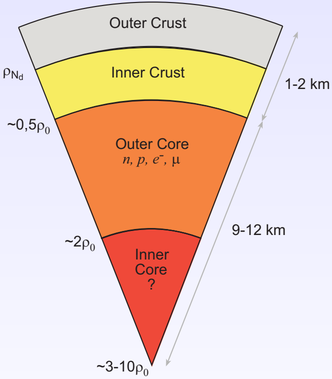


- The core is composed of uniform nuclear matter under the β-stability and the charge neutrality conditions:

$$\textit{The composition: } (n,\ p,\ e^-,\ \mu^-)$$

- The outer crust is the outermost region of the crust. It comprises densities between $10^4 \text{g}/\text{cm}^3$ and $4 \cdot 10^{11} \text{g}/\text{cm}^3$ and it is composed of atomic nuclei and a Fermi gas of free electrons

Structure of a Neutron Star



- The core is composed of uniform nuclear matter under the β-stability and the charge neutrality conditions:

$$\textit{The composition:}\ (n,\ p,\ e^-,\ \mu^-)$$

- The outer crust is the outermost region of the crust. It comprises densities between $10^4 \mathrm{g/cm}^3$ and $4 \cdot 10^{11} \mathrm{g/cm}^3$ and it is composed of atomic nuclei and a Fermi gas of free electrons
- As density increases, the nuclei become more neutron-rich until the strong nuclear force can not bind such a big neutron excess → neutron drip → frontier of the inner crust

The Aim of This Work

- To compute the composition of the outer crust of a neutron star
- To study the sensitivity of the results with respect the nuclear masses that are not experimentally available and need to be predicted using nuclear models
- To determine the nuclei that have the greatest impact and that would be of interest to be measured next in the laboratories

The Aim of This Work

- To compute the composition of the outer crust of a neutron star
- To study the sensitivity of the results with respect the nuclear masses that are not experimentally available and need to be predicted using nuclear models
- To determine the nuclei that have the greatest impact and that would be of interest to be measured next in the laboratories

Note: The problem of the outer crust is related to

The Aim of This Work

- To compute the composition of the outer crust of a neutron star
- To study the sensitivity of the results with respect the nuclear masses that are not experimentally available and need to be predicted using nuclear models
- To determine the nuclei that have the greatest impact and that would be of interest to be measured next in the laboratories

Note: The problem of the outer crust is related to

- The determination of the equation of state of neutron-rich matter, which can not be synthesised in terrestrial laboratories
- Complete the Chart of Nuclides. Mapping the composition of the outer crust is strongly dependent on the neutron-rich nuclei with $Z \sim 20 - 50$ near the $N = 50$ and $N = 82$ shell closures

Selected Elements of the Formalism (I)

- The formalism followed here is the one established by Baym, Pethick and Sutherland (BPS) [AJ **170**, 299 (1971)], as applied more recently by Rüster, Hempel and Schaffner-Bielich [PRC **73**, 035804 (2006)] and by Roca-Maza and Piekarewicz [PRC **78**, 025807 (2008)]

Selected Elements of the Formalism (I)

- The formalism followed here is the one established by Baym, Pethick and Sutherland (BPS) [AJ **170**, 299 (1971)], as applied more recently by Rüster, Hempel and Schaffner-Bielich [PRC **73**, 035804 (2006)] and by Roca-Maza and Piekarewicz [PRC **78**, 025807 (2008)]
- One assumes that the outer crust is composed of atomic nuclei arranged in a body-centred cubic (bcc) lattice and a Fermi gas of the free electrons

Selected Elements of the Formalism (I)

- The formalism followed here is the one established by Baym, Pethick and Sutherland (BPS) [AJ **170**, 299 (1971)], as applied more recently by Rüster, Hempel and Schaffner-Bielich [PRC **73**, 035804 (2006)] and by Roca-Maza and Piekarewicz [PRC **78**, 025807 (2008)]

- One assumes that the outer crust is composed of atomic nuclei arranged in a body-centred cubic (bcc) lattice and a Fermi gas of the free electrons

- The goal: To find the Z and N numbers of the nuclei which, at every layer of the outer crust, minimise the energy per baryon of the system

$$\boxed{\varepsilon(\mathbf{A},\mathbf{Z};\mathbf{n}) = \varepsilon_{\mathbf{nuclear}} + \varepsilon_{\mathbf{electronic}} + \varepsilon_{\mathbf{lattice}}}$$

where n is the number of baryons per unit volume and $A = Z + N$

Selected Elements of the Formalism (I)

- The formalism followed here is the one established by Baym, Pethick and Sutherland (BPS) [AJ **170**, 299 (1971)], as applied more recently by Rüster, Hempel and Schaffner-Bielich [PRC **73**, 035804 (2006)] and by Roca-Maza and Piekarewicz [PRC **78**, 025807 (2008)]

- One assumes that the outer crust is composed of atomic nuclei arranged in a body-centred cubic (bcc) lattice and a Fermi gas of the free electrons

- The goal: To find the Z and N numbers of the nuclei which, at every layer of the outer crust, minimise the energy per baryon of the system

$$\boxed{\varepsilon(\mathbf{A},\mathbf{Z};\mathbf{n}) = \varepsilon_{\mathbf{nuclear}} + \varepsilon_{\mathbf{electronic}} + \varepsilon_{\mathbf{lattice}}}$$

where n is the number of baryons per unit volume and $A = Z + N$

- The basic assumption:

The physical system considered is in equilibrium,

what implies that the pressure and chemical potential are continuous throughout the outer crust

Selected Elements of the Formalism (II)

- The pressure of the system takes into account the electronic Fermi gas and the lattice contributions

Selected Elements of the Formalism (II)

- The pressure of the system takes into account the electronic Fermi gas and the lattice contributions
- In a good approximation the system can be assumed a T=0

Selected Elements of the Formalism (II)

- The pressure of the system takes into account the electronic Fermi gas and the lattice contributions
- In a good approximation the system can be assumed a T=0
- The chemical potential is [PRC **78**, 025807 (2008)]:

$$\mu(\mathbf{A},\mathbf{Z},\mathbf{P}) \;=\; \varepsilon(\mathbf{A},\mathbf{Z};\mathbf{n})+\frac{\mathbf{P}}{\mathbf{n}}=\frac{\mathbf{M}(\mathbf{A},\mathbf{Z})}{\mathbf{A}}+\frac{\mathbf{Z}}{\mathbf{A}}\mu_{\mathbf{e}}-\frac{4}{3}\mathbf{C}_{\mathbf{l}}\frac{\mathbf{Z}^2}{\mathbf{A}^{4/3}}\mathbf{p}_{\mathbf{F}}$$

where $\mu_e = \sqrt{p_e^2+m_e^2}$ is the chemical potential of the electrons, p_e is the Fermi momentum of the electrons and p_F is the Fermi momentum of nucleon

Selected Elements of the Formalism (II)

- The pressure of the system takes into account the electronic Fermi gas and the lattice contributions

- In a good approximation the system can be assumed a T=0

- The chemical potential is [PRC **78**, 025807 (2008)]:

$$\boldsymbol{\mu(A,Z,P) \;=\; \varepsilon(A,Z;n) + \frac{P}{n} = \frac{M(A,Z)}{A} + \frac{Z}{A}\mu_e - \frac{4}{3}C_l\frac{Z^2}{A^{4/3}}p_F}$$

where $\mu_e = \sqrt{p_e^2 + m_e^2}$ is the chemical potential of the electrons, p_e is the Fermi momentum of the electrons and p_F is the Fermi momentum of nucleon

- The pressure is continuous throughout the outer crust and it is useful to take it as our independent variable and to minimise the chemical potential as a function of N and Z numbers (equilibrium condition).

The Nuclear Mass Calculation

- The nuclear masses are expressed as follows [cf. e.g. Audi, Wang et al., CPC **36**, p. 1287 (2012)]:

$$\boxed{\mathbf{M(N, Z) = A \cdot au + ME - Z \cdot m_e + B_{el}(Z)}}$$

where "au" is the atomic mass unit, ME is the nuclear mass excess and $B_{el}(Z)$ is the binding energy of the removed electrons

The Nuclear Mass Calculation

- The nuclear masses are expressed as follows [cf. e.g. Audi, Wang et al., CPC **36**, p. 1287 (2012)]:

$$\boxed{\mathbf{M(N,Z) = A \cdot au + ME - Z \cdot m_e + B_{el}(Z)}}$$

where "au" is the atomic mass unit, ME is the nuclear mass excess and $B_{el}(Z)$ is the binding energy of the removed electrons

- We have taken the newest experimental values of the nuclear mass excess from the Atomic Mass Evaluation data base (AME2012)

The Nuclear Mass Calculation

- The nuclear masses are expressed as follows [cf. e.g. Audi, Wang et al., CPC **36**, p. 1287 (2012)]:

$$\boxed{\mathbf{M(N,Z) = A \cdot au + ME - Z \cdot m_e + B_{el}(Z)}}$$

where "au" is the atomic mass unit, ME is the nuclear mass excess and $B_{el}(Z)$ is the binding energy of the removed electrons

- We have taken the newest experimental values of the nuclear mass excess from the Atomic Mass Evaluation data base (AME2012)

- Since not all nuclear masses of interest for the outer crust are known experimentally, we have completed the missing ones with theoretical results (using Skyrme Hartree-Fock-Bogolyubov approach, HFB19, HFB21)

The Nuclear Mass Calculation

- The nuclear masses are expressed as follows [cf. e.g. Audi, Wang et al., CPC **36**, p. 1287 (2012)]:

$$\boxed{\mathbf{M(N,Z) = A \cdot au + ME - Z \cdot m_e + B_{el}(Z)}}$$

where $"\mathrm{au}"$ is the atomic mass unit, ME is the nuclear mass excess and $B_{el}(Z)$ is the binding energy of the removed electrons

- We have taken the newest experimental values of the nuclear mass excess from the Atomic Mass Evaluation data base (AME2012)

- Since not all nuclear masses of interest for the outer crust are known experimentally, we have completed the missing ones with theoretical results (using Skyrme Hartree-Fock-Bogolyubov approach, HFB19, HFB21)

- The most recent experimental result of the mass excess of ^{82}Zn nucleus [cf. Wolf et al., PRL **110**, 04110 (2013)] has been also introduced as a check

Brief Description of HFB19 and HFB21 Parameterisations

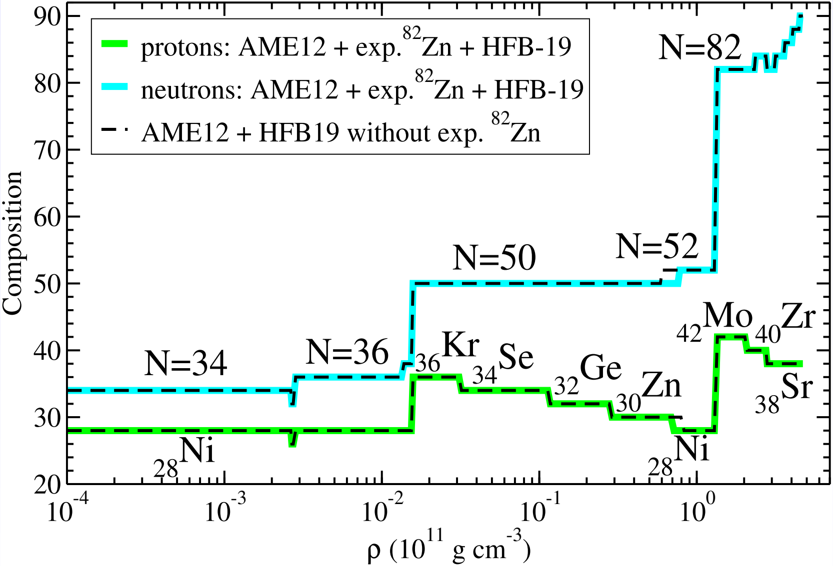
- HFB19 and HFB21 parameterisations used are applied within the Hartree-Fock-Bogolyubov (HFB) Method. They are among the most recent Skyrme models [Pearson et al. PRC **83**, 065810 (2011)]

- In the Skyrme parameterisations used, the parameters have been fitted to the experimental masses available from the 2003 Atomic Mass Evaluation and taking into account microscopic calculations of the equation of state of neutron matter

- They fit the experimental data on the nuclear masses with a r.m.s. deviation of 0.58 MeV, the best result in this kind of calculations

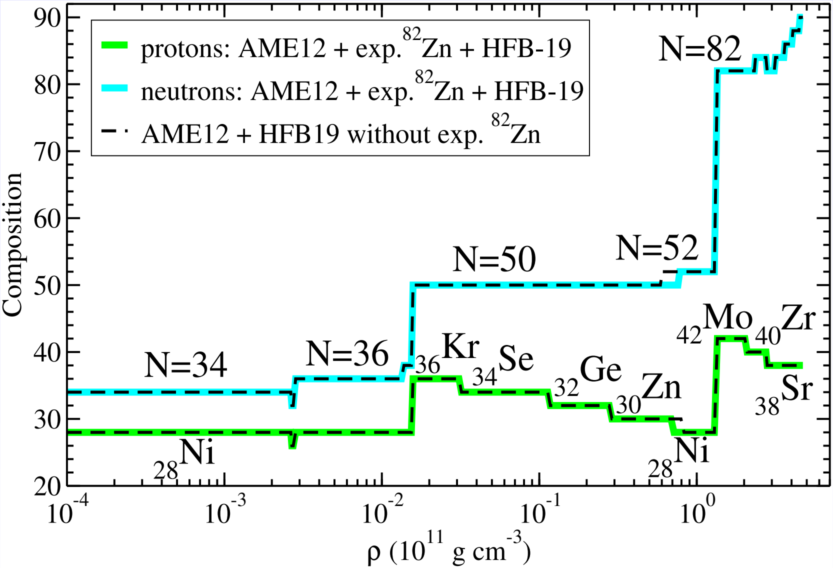
- For these reasons, HFB19 and HFB21 are considered very appropriate parameterisations for studies of neutron-rich matter and of the outer crust of a neutron star

Resulting crust composition using HFB-19



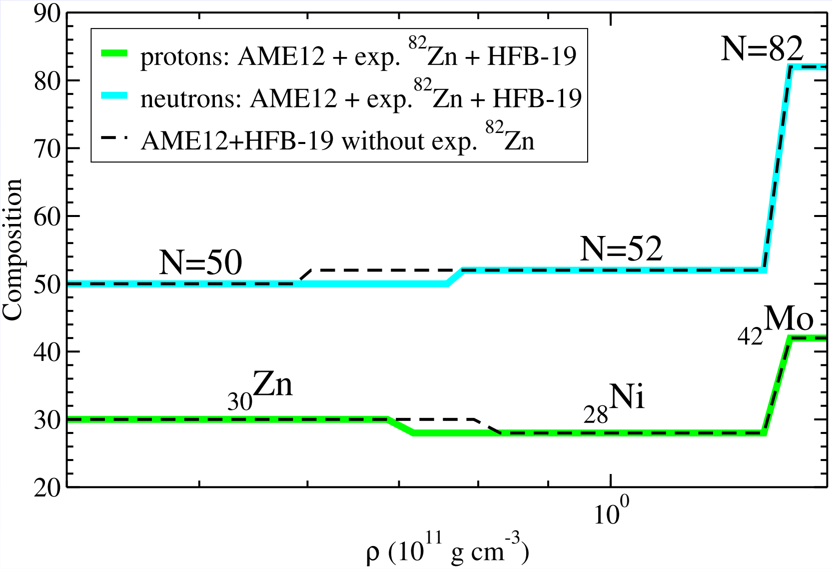
- For low densities: the resulting nuclei are taken from AME2012
- For high densities: the resulting nuclei are taken from HFB-19

Resulting crust composition using HFB-19



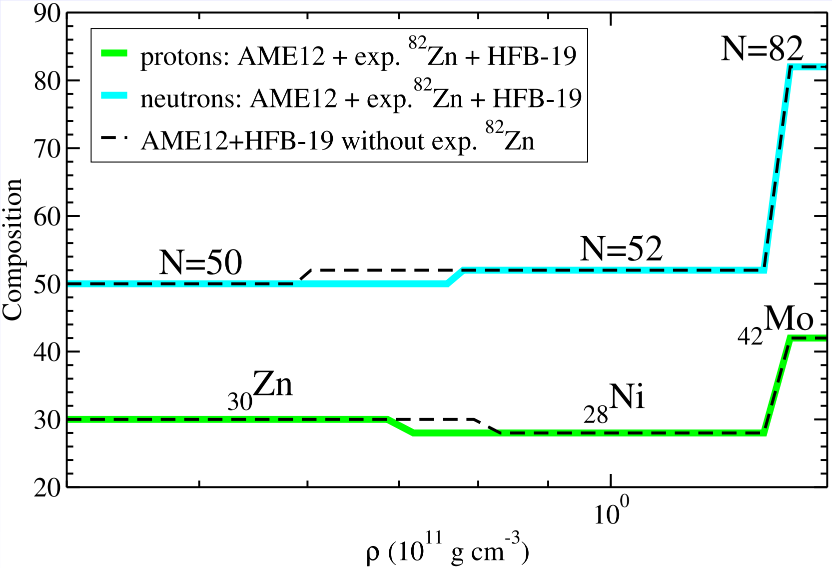
- The resulting composition has changed when replacing the HFB-19 value of the ^{82}Zn mass excess by the experimental value (Wolf, PRL 110)

Detail of the resulting crust composition using HFB-19



- With $\mathrm{ME}_{19}(^{82}\mathrm{Zn}) = -42.96\ \mathrm{MeV}/c^2$ we obtain: ^{80}Zn – ^{82}Zn – ^{80}Ni
- With $\mathrm{ME}_{\mathrm{exp}}(^{82}\mathrm{Zn}) = -42.314\ \mathrm{MeV}/c^2$ we obtain: ^{80}Zn – ^{78}Ni – ^{80}Ni

Detail of the resulting crust composition using HFB-19



- Mass variation of ^{82}Zn: $\mathrm{ME}_{\mathrm{exp}} - \mathrm{ME}_{19} = 0.65\ \mathrm{MeV}/c^2 \Longrightarrow$ This shows a sensitivity on the masses of the nuclei in this region

Dependence on unknown nuclear masses (I)

• We studied the chemical potentials of the nuclei in the vicinities of the nuclei ^{80}Zn, ^{78}Ni and ^{80}Ni in the ranges of $Z_o \pm 4$ and $N_o \pm 4$, and for this purpose we constructed two subsets of nuclei:

- Nuclei around ^{80}Zn
- Nuclei around ^{80}Ni

Dependence on unknown nuclear masses (I)

• We studied the chemical potentials of the nuclei in the vicinities of the nuclei ^{80}Zn, ^{78}Ni and ^{80}Ni in the ranges of $Z_o \pm 4$ and $N_o \pm 4$, and for this purpose we constructed two subsets of nuclei:

- Nuclei around ^{80}Zn
- Nuclei around ^{80}Ni

• With this choice, we scanned the results for a mesh of pressures along the shells of ^{80}Zn, ^{78}Ni and ^{80}Ni. We have been able to identify the nuclei that have the closer chemical potential to these listed nuclei.

Dependence on unknown nuclear masses (I)

• We studied the chemical potentials of the nuclei in the vicinities of the nuclei ^{80}Zn, ^{78}Ni and ^{80}Ni in the ranges of $Z_o \pm 4$ and $N_o \pm 4$, and for this purpose we constructed two subsets of nuclei:

- Nuclei around ^{80}Zn
- Nuclei around ^{80}Ni

• With this choice, we scanned the results for a mesh of pressures along the shells of ^{80}Zn, ^{78}Ni and ^{80}Ni. We have been able to identify the nuclei that have the closer chemical potential to these listed nuclei.

• For a better identification we have ordered the nuclei in increasing chemical potential and we have labelled the nuclei with "0" when the mass excess of the nucleus has been taken from the HFB-19 theoretical prediction, and with "1" when the mass excess of the nucleus is taken from AME2012 (or from Wolf et al., PRL **110**, 04110(2013) for the case of ^{82}Zn).

Dependence on unknown nuclear masses (II)

$P = 1.770 \cdot 10^{-5}$ MeV/c^2; start of the ^{80}Zn shell

I/O	ρ (10^{11}g/cm^3)	Z	N	A	ME (MeV/c^2)	$\mu - m_n$ (MeV)
1	0.289495	30	50	80	−51.649	−4.816579
1	0.278609	32	50	82	−65.415	−4.816540
1	0.282258	30	48	78	−57.483	−4.807928
1	0.285404	32	52	84	−58.148	−4.807527
1	0.283874	31	50	81	−57.628	−4.805316
1	0.285876	30	49	79	−53.432	−4.797959
0	0.288026	29	48	77	−49.58	−4.794857
0	0.294209	28	48	76	−42.47	−4.792063
1	0.275420	34	52	86	−70.503	−4.791911
1	0.281826	34	54	88	−63.884	−4.791227

- As a first example, we present the results obtained at a pressure $P = 1.770 \cdot 10^{-5}$ MeV/c^2, i.e. at the beginning of the ^{80}Zn shell.

Dependence on unknown nuclear masses (II)

$P = 1.770 \cdot 10^{-5}$ MeV/c^2; start of the ^{80}Zn shell

I/O	ρ (10^{11}g/cm^3)	Z	N	A	ME (MeV/c^2)	$\mu - m_n$ (MeV)
1	0.289495	30	50	80	−51.649	−4.816579
1	0.278609	32	50	82	−65.415	−4.816540
1	0.282258	30	48	78	−57.483	−4.807928
1	0.285404	32	52	84	−58.148	−4.807527
1	0.283874	31	50	81	−57.628	−4.805316
1	0.285876	30	49	79	−53.432	−4.797959
0	0.288026	29	48	77	−49.58	−4.794857
0	0.294209	28	48	76	−42.47	−4.792063
1	0.275420	34	52	86	−70.503	−4.791911
1	0.281826	34	54	88	−63.884	−4.791227

- The ^{82}Ge nucleus competes head-to-head with ^{80}Zn for being at the ground state at this pressure. Their chemical potential differ in only 39 eV.

Dependence on unknown nuclear masses (II)

$P = 1.770 \cdot 10^{-5}$ MeV/c^2; start of the ^{80}Zn shell

I/O	ρ (10^{11}g/cm^3)	Z	N	A	ME (MeV/c^2)	$\mu - m_n$ (MeV)
1	0.289495	30	50	80	−51.649	−4.816579
1	0.278609	32	50	82	−65.415	−4.816540
1	0.282258	30	48	78	−57.483	−4.807928
1	0.285404	32	52	84	−58.148	−4.807527
1	0.283874	31	50	81	−57.628	−4.805316
1	0.285876	30	49	79	−53.432	−4.797959
0	0.288026	29	48	77	−49.58	−4.794857
0	0.294209	28	48	76	−42.47	−4.792063
1	0.275420	34	52	86	−70.503	−4.791911
1	0.281826	34	54	88	−63.884	−4.791227

- In this case, only two nuclei (^{77}Cu and ^{76}Ni) have their mass *unknown*
$\Longrightarrow$ the composition can be treated *practically as an experimental fact*.

Dependence on unknown nuclear masses (III)

$P = 6.072 \cdot 10^{-5}$ MeV$/c^2$; start of the ^{80}Ni shell

I/O	ρ (10^{11}g/cm^3)	Z	N	A	ME (MeV$/c^2$)	$\mu - m_n$ (MeV)
0	0.780025	28	52	80	−24.00	−3.348607
0	0.760524	28	50	78	−33.44	−3.348537
1	0.747378	30	52	82	−42.314	−3.345454
0	0.744291	29	50	79	−42.44	−3.344794
0	0.763134	29	52	81	−32.98	−3.344708
0	0.765607	30	54	84	−32.76	−3.344236
1	0.729149	30	50	80	−51.649	−3.343990
0	0.770275	28	51	79	−28.32	−3.343509
0	0.741024	28	48	76	−42.47	−3.343069
0	0.750774	28	49	77	−37.27	−3.336943

- The ^{78}Ni isotope is the nucleus that disputes the ground state with ^{80}Ni. Their chemical potential differ only in 70 eV.

Dependence on unknown nuclear masses (III)

$P = 6.072 \cdot 10^{-5}$ MeV/c^2; start of the ^{80}Ni shell

I/O	ρ (10^{11}g/cm^3)	Z	N	A	ME (MeV/c^2)	$\mu - m_n$ (MeV)
0	0.780025	28	52	80	−24.00	−3.348607
0	0.760524	28	50	78	−33.44	−3.348537
1	0.747378	30	52	82	−42.314	−3.345454
0	0.744291	29	50	79	−42.44	−3.344794
0	0.763134	29	52	81	−32.98	−3.344708
0	0.765607	30	54	84	−32.76	−3.344236
1	0.729149	30	50	80	−51.649	−3.343990
0	0.770275	28	51	79	−28.32	−3.343509
0	0.741024	28	48	76	−42.47	−3.343069
0	0.750774	28	49	77	−37.27	−3.336943

- Some important experimental achievements have been carried out in detecting and measuring the half-live of ^{78}Ni and ^{80}Ni.

Dependence on unknown nuclear masses (III)

$P = 6.072 \cdot 10^{-5}$ MeV$/c^2$; start of the ^{80}Ni shell

I/O	ρ (10^{11}g/cm^3)	Z	N	A	ME (MeV$/c^2$)	$\mu - m_n$ (MeV)
0	0.780025	28	52	80	−24.00	−3.348607
0	0.760524	28	50	78	−33.44	−3.348537
1	0.747378	30	52	82	−42.314	−3.345454
0	0.744291	29	50	79	−42.44	−3.344794
0	0.763134	29	52	81	−32.98	−3.344708
0	0.765607	30	54	84	−32.76	−3.344236
1	0.729149	30	50	80	−51.649	−3.343990
0	0.770275	28	51	79	−28.32	−3.343509
0	0.741024	28	48	76	−42.47	−3.343069
0	0.750774	28	49	77	−37.27	−3.336943

- Now, most of the nuclei have their masses experimentally *unknown*; only two nuclei (^{82}Zn and ^{80}Zn) have their mass excess measured.

Dependence on unknown nuclear masses (IV)

- With study we have been able to identify the nuclei of interest **in the region between the $\mathbf{N = 50 - 52}$ and $\mathbf{N = 82}$ plateaux**

- We have scanned the results to different pressures along the shells of ^{80}Zn, ^{78}Ni and ^{80}Ni. We have taken into account the position that the nuclei took in the chemical potential tables

Dependence on unknown nuclear masses (IV)

- With study we have been able to identify the nuclei of interest **in the region between the $N = 50 - 52$ and $N = 82$ plateaux**

- We have scanned the results to different pressures along the shells of ^{80}Zn, ^{78}Ni and ^{80}Ni. We have taken into account the position that the nuclei took in the chemical potential tables

- The set of nuclei of importance found is:

$^{76-82}$Ni,$^{79-81}$Cu, ^{83,84}Zn, ^{86}Ge,

$^{122-126}$Mo, ^{125}Tc,$^{126-128}$Ru, and ^{128,130}Pd.

Dependence on unknown nuclear masses (IV)

- With study we have been able to identify the nuclei of interest **in the region between the $N = 50 - 52$ and $N = 82$ plateaux**

- We have scanned the results to different pressures along the shells of ^{80}Zn, ^{78}Ni and ^{80}Ni. We have taken into account the position that the nuclei took in the chemical potential tables

- The set of nuclei of importance found is:

$^{76-82}$Ni,$^{79-81}$Cu, ^{83,84}Zn, ^{86}Ge,

$^{122-126}$Mo, ^{125}Tc,$^{126-128}$Ru, and ^{128,130}Pd.

- All these nuclei have *unknown experimental mass*

Dependence on unknown nuclear masses (IV)

- With study we have been able to identify the nuclei of interest **in the region between the N = 50 − 52 and N = 82 plateaux**

- We have scanned the results to different pressures along the shells of ^{80}Zn, ^{78}Ni and ^{80}Ni. We have taken into account the position that the nuclei took in the chemical potential tables

- The set of nuclei of importance found is:

$$\mathbf{^{76-82}Ni, ^{79-81}Cu,\ ^{83,84}Zn,\ ^{86}Ge,}$$

$$\mathbf{^{122-126}Mo,\ ^{125}Tc, ^{126-128}Ru, \text{ and } ^{128,130}Pd.}$$

- All these nuclei have *unknown experimental mass*

- We varied their theoretical mass excess up to they appeared in or disappeared from the composition pattern of the outer crust

Model mass excess variation

Nuclei with $Z = 28 - 30$

Z	N	A	ME_{19} (MeV/c^2)	ME_{v} (MeV/c^2)	$\Delta\mathrm{ME}$ (MeV/c^2)	Appear/Disappear	Last known mass
28	48	76	−42.47	−42.68	−0.21	Appear (after ^{80}Zn)	^{73}Ni
28	49	77	−37.27	−38.06	−0.79	Appear (after ^{80}Zn)	^{73}Ni
28	50	78	−33.44	−33.31	0.13	Disappear (after ^{80}Zn)	^{73}Ni
28	51	79	−28.32	−28.73	−0.41	Appear (after ^{78}Ni)	^{73}Ni
28	52	80	−24.00	−23.28	0.78	Disappear (after ^{78}Ni)	^{73}Ni
28	54	82	−12.33	−12.64	−0.31	Appear (after ^{80}Ni)	^{73}Ni
29	50	79	−42.44	−42.56	−0.12	Appear (after ^{80}Zn)	^{76}Cu, ^{78}Cu
29	52	81	−32.98	−33.30	−0.32	Appear (after ^{78}Ni)	^{76}Cu, ^{78}Cu
30	54	84	−32.76	−33.13	−0.37	Appear (after ^{78}Ni)	^{82}Zn

Nuclei with $Z = 42 - 46$

Z	N	A	ME_{19} (MeV/c^2)	ME_{v} (MeV/c^2)	$\Delta\mathrm{ME}$ (MeV/c^2)	Appear/Disappear	Last known mass
42	82	124	−5.80	−4.65	1.15	Disappear (after ^{80}Ni)	^{111}Mo
43	82	125	−15.51	−16.52	−1.01	Appear (after ^{80}Ni)	^{113}Tc
44	82	126	−27.14	−27.22	−0.08	Appear (after ^{80}Ni)	^{117}Ru
44	84	128	−14.92	−15.86	−0.94	Appear (after ^{80}Ni)	^{117}Ru
46	82	128	−46.09	−46.88	−0.79	Appear (after ^{78}Ni)	^{122}Pd

Model mass excess variation

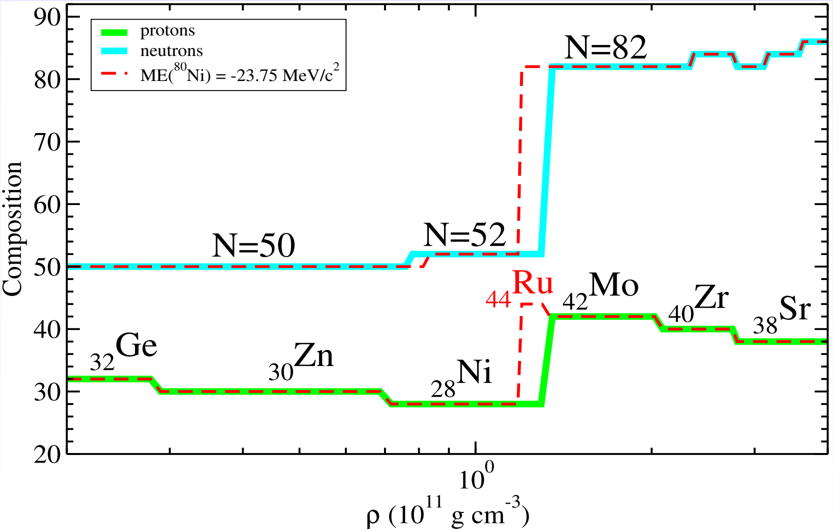
Nuclei with $Z = 28 - 30$

Z	N	A	ME$_{19}$ (MeV/c^2)	ME$_\mathrm{v}$ (MeV/c^2)	ΔME (MeV/c^2)	Appear/Disappear	Last known mass
28	48	76	-42.47	-42.68	-0.21	Appear (after ^{80}Zn)	^{73}Ni
28	49	77	-37.27	-38.06	-0.79	Appear (after ^{80}Zn)	^{73}Ni
28	50	78	-33.44	-33.31	0.13	Disappear (after ^{80}Zn)	^{73}Ni
28	51	79	-28.32	-28.73	-0.41	Appear (after ^{78}Ni)	^{73}Ni
28	52	80	-24.00	-23.28	0.78	Disappear (after ^{78}Ni)	^{73}Ni
28	54	82	-12.33	-12.64	-0.31	Appear (after ^{80}Ni)	^{73}Ni
29	50	79	-42.44	-42.56	-0.12	Appear (after ^{80}Zn)	^{76}Cu, ^{78}Cu
29	52	81	-32.98	-33.30	-0.32	Appear (after ^{78}Ni)	^{76}Cu, ^{78}Cu
30	54	84	-32.76	-33.13	-0.37	Appear (after ^{78}Ni)	^{82}Zn

Nuclei with $Z = 42 - 46$

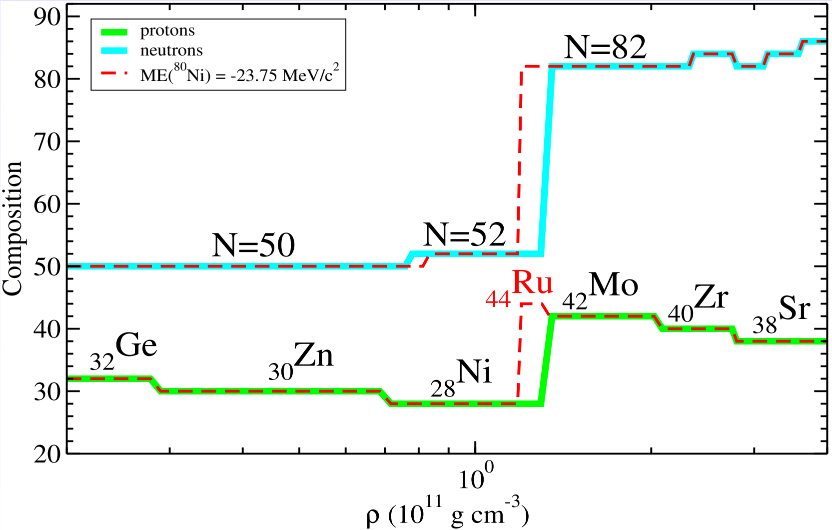
Z	N	A	ME$_{19}$ (MeV/c^2)	ME$_\mathrm{v}$ (MeV/c^2)	ΔME (MeV/c^2)	Appear/Disappear	Last known mass
42	82	124	-5.80	-4.65	1.15	Disappear (after ^{80}Ni)	^{111}Mo
43	82	125	-15.51	-16.52	-1.01	Appear (after ^{80}Ni)	^{113}Tc
44	82	126	-27.14	-27.22	-0.08	Appear (after ^{80}Ni)	^{117}Ru
44	84	128	-14.92	-15.86	-0.94	Appear (after ^{80}Ni)	^{117}Ru
46	82	128	-46.09	-46.88	-0.79	Appear (after ^{78}Ni)	^{122}Pd

Studying the change of the range of densities of ^{80}Ni



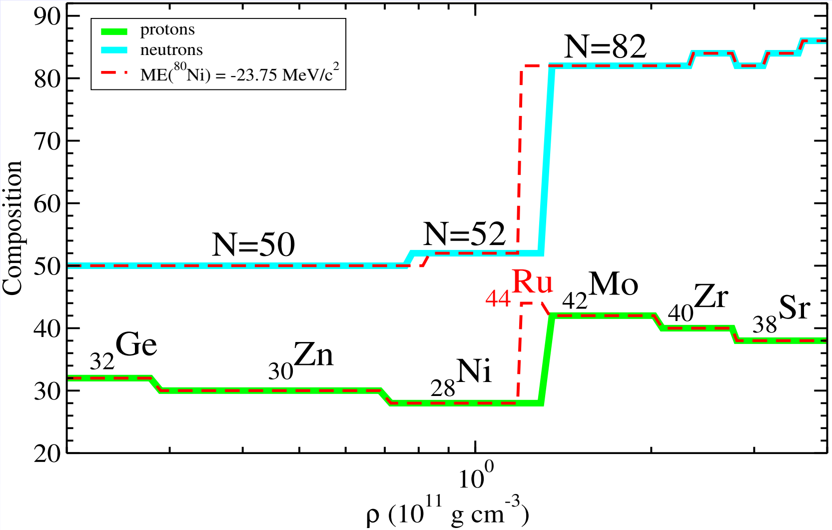
- We have varied in $+0.25$ MeV$/c^2$ the mass excess prediction of ^{80}Ni, from -24.00 MeV$/c^2$ to -23.75 MeV$/c^2$.

Studying the change of the range of densities of ^{80}Ni



- The range of densities of ^{80}Ni **has decreased in around ∼ 30%** because now the mass excess of this nucleus is less bound and thus, less energetically favorable for the system.

Studying the change of the range of densities of ^{80}Ni



- In addition, a nucleus that was not predicted before appears in the composition, namely the ^{126}Ru nucleus ⟹ **Even a marginal variation in the mass excess of ^{80}Ni can dramatically change the composition**

Shortlist of the nuclei of greatest impact

Z	N	A	ME_{19} (MeV/c^2)	$\Delta\mathrm{ME}_{19}$ (MeV/c^2)	ME_{21} (MeV/c^2)	$\Delta\mathrm{ME}_{21}$ (MeV/c^2)
28	48	76	−42.47	−0.21	−42.96	−0.26
28	50	78	−33.44	0.13	−34.04	0.33
28	51	79	−28.32	−0.41	−28.79	−0.23
28	52	80	−24.00	0.78	−23.98	0.69
28	54	82	−12.33	−0.31	−11.64	−0.86
29	50	79	−42.44	−0.12	−43.27	0.37
29	52	81	−32.98	−0.32	−32.92	−0.92
30	54	84	−32.76	−0.37	−32.09	−1.51
42	82	124	−5.80	1.15	−5.44	1.58
43	82	125	−15.51	−1.01	−15.28	−0.99
44	82	126	−27.14	−0.08	−26.43	−0.65
46	82	128	−46.09	−0.79	−45.65	−1.74

- Carrying out the same calculations with HFB-21, we have been able to cross the results obtained with both models and finally we have obtained a list of the nuclei with the greatest impact on the outer of a neutron star.

Shortlist of the nuclei of greatest impact

Z	N	A	ME_{19} (MeV/c^2)	$\Delta\mathrm{ME}_{19}$ (MeV/c^2)	ME_{21} (MeV/c^2)	$\Delta\mathrm{ME}_{21}$ (MeV/c^2)
28	48	76	−42.47	−0.21	−42.96	−0.26
28	50	78	−33.44	0.13	−34.04	0.33
28	51	79	−28.32	−0.41	−28.79	−0.23
28	52	80	−24.00	0.78	−23.98	0.69
28	54	82	−12.33	−0.31	−11.64	−0.86
29	50	79	−42.44	−0.12	−43.27	0.37
29	52	81	−32.98	−0.32	−32.92	−0.92
30	54	84	−32.76	−0.37	−32.09	−1.51
42	82	124	−5.80	1.15	−5.44	1.58
43	82	125	−15.51	−1.01	−15.28	−0.99
44	82	126	−27.14	−0.08	−26.43	−0.65
46	82	128	−46.09	−0.79	−45.65	−1.74

- It would be of great importance to measure the mass of these nuclei in the different radioactive beam facilities that operate worldwide

Shortlist of the nuclei of greatest impact

Z	N	A	ME_{19} (MeV/c^2)	$\Delta\mathrm{ME}_{19}$ (MeV/c^2)	ME_{21} (MeV/c^2)	$\Delta\mathrm{ME}_{21}$ (MeV/c^2)
28	48	76	−42.47	−0.21	−42.96	−0.26
28	50	78	−33.44	0.13	−34.04	0.33
28	51	79	−28.32	−0.41	−28.79	−0.23
28	52	80	−24.00	0.78	−23.98	0.69
28	54	82	−12.33	−0.31	−11.64	−0.86
29	50	79	−42.44	−0.12	−43.27	0.37
29	52	81	−32.98	−0.32	−32.92	−0.92
30	54	84	−32.76	−0.37	−32.09	−1.51
42	82	124	−5.80	1.15	−5.44	1.58
43	82	125	−15.51	−1.01	−15.28	−0.99
44	82	126	−27.14	−0.08	−26.43	−0.65
46	82	128	−46.09	−0.79	−45.65	−1.74

- Most of these nuclei have been discovered (highlighted with yellow) and their half-live have been measured (highlighted with pink)

Conclusions

- There is a dependence on the models used in the predicted composition of the outer crust.

Conclusions

- There is a dependence on the models used in the predicted composition of the outer crust.

- The inclusion of a new mass measurement (in this case, that of ^{82}Zn) has showed us that there is also a dependence on small variations on the mass excess of the involved nuclei.

Conclusions

- There is a dependence on the models used in the predicted composition of the outer crust.

- The inclusion of a new mass measurement (in this case, that of ^{82}Zn) has showed us that there is also a dependence on small variations on the mass excess of the involved nuclei.

- Generally, our study has shown that a variation less than 0.5 MeV/c^2 applied on the mass excess of the nuclei of interest suffices to change the composition profile. This variation is smaller than that between the theoretical prediction of the mass excess of the ^{82}Zn nucleus and the experimental value (Wolf et al., PRL **110**, 04110 (2013)).

Conclusions

- There is a dependence on the models used in the predicted composition of the outer crust.

- The inclusion of a new mass measurement (in this case, that of ^{82}Zn) has showed us that there is also a dependence on small variations on the mass excess of the involved nuclei.

- Generally, our study has shown that a variation less than 0.5 MeV/c^2 applied on the mass excess of the nuclei of interest suffices to change the composition profile. This variation is smaller than that between the theoretical prediction of the mass excess of the ^{82}Zn nucleus and the experimental value (Wolf et al., PRL **110**, 04110 (2013)).

- We have identified the nuclei which have the greatest impact on the composition pattern and which would be of great importance to be next measured in the experimental facilities of all around the world.

Thank you for your attention!