 

PYCNONUCLEAR REACTIONS

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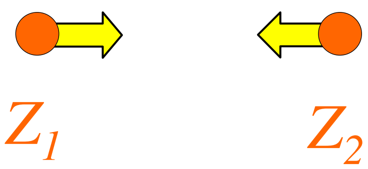
1. Thermonuclear reactions
2. Pycnonuclear reactions
3. Nuclear physics and neutron star crust

ALMAS1, October 19-20, 2006

Classical theory of thermonuclear reactions

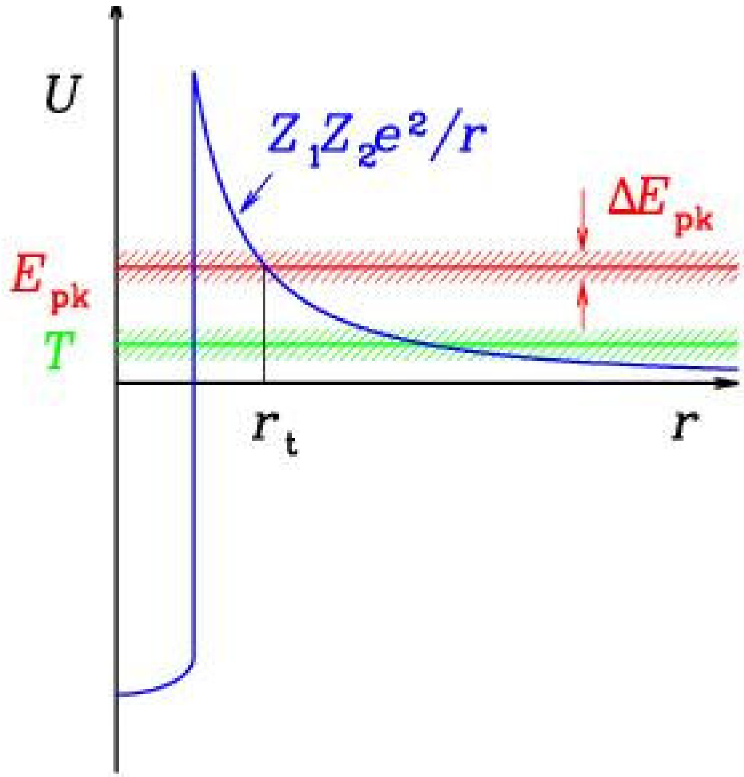
$$Z_1 + Z_2 \to Z_c \to \ldots$$

Reaction rate:



$$R = \frac{n_1 n_2}{1+\delta_{12}} \langle v\sigma \rangle \qquad \frac{\textbf{reactions}}{\textbf{cm}^3\ \textbf{s}}$$

$$\int_0^\infty \mathbf{d}v \ \ v^3 \ \ \mathbf{e}^{-E/T} \sigma(E)$$



$$\sigma(E) = \frac{S(E)P(E)}{E}, \qquad P(E) = \exp(-\eta)$$

$$\eta(E) = \frac{2}{\hbar} \int_b^a \mathrm{d}r \ \ |p(r)| = \frac{2\pi Z_1 Z_2 e^2}{\hbar v}$$

Classical theory of thermonuclear reactions

$$\langle v\sigma \rangle = 4\sqrt{\frac{2E_{pk}}{3M}}\;\frac{S(E_{pk})}{T}\;\mathbf{exp}(-\tau)$$

$$\tau = \frac{3E_{pk}}{T} = \left(\frac{27\pi^2 M Z_1^2 Z_2^2 e^4}{2T\hbar^2}\right)^{1/3} \gg 1$$

Reaction rate *R* depends mainly on *T*

Nobel Prize, 1967

- **History** (**1938**) → **G. Gamow, H. Bethe, C. Critchfield, E. Salpeter, C. Von Weizsacker, A. Cameron, W. Fowler, G. Rivers**
- **Example** → ***Carbon burning:*** $^{12}\mathrm{C} + {}^{12}\mathrm{C} \Rightarrow {}^{24}\mathrm{Mg}^* \Rightarrow \ldots$

$\rho = 10^9$ g cm^{-3}, $t = n_i / R$ **= burning time**

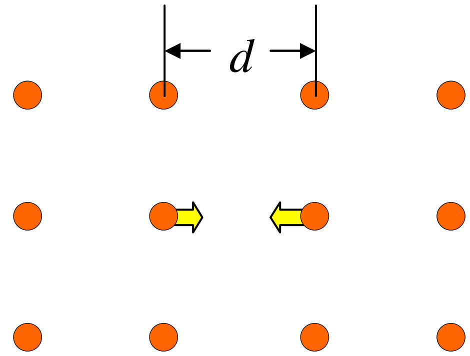
T=10^9 K → t~ 1 min

T=10^8 K → t~10^{36} yr

No burning at low *T*!

Pycnonuclear reactions

Coulomb lattice of nuclei, *T*=0



Zero-point vibrations, $E \sim \hbar\omega, \quad r_0 \sim \sqrt{\dfrac{\hbar}{m\omega}}$

$$\omega \sim \omega_p = \sqrt{\frac{4\pi Z^2 e^2 n_i}{m}}$$ *=ion plasma frequency*

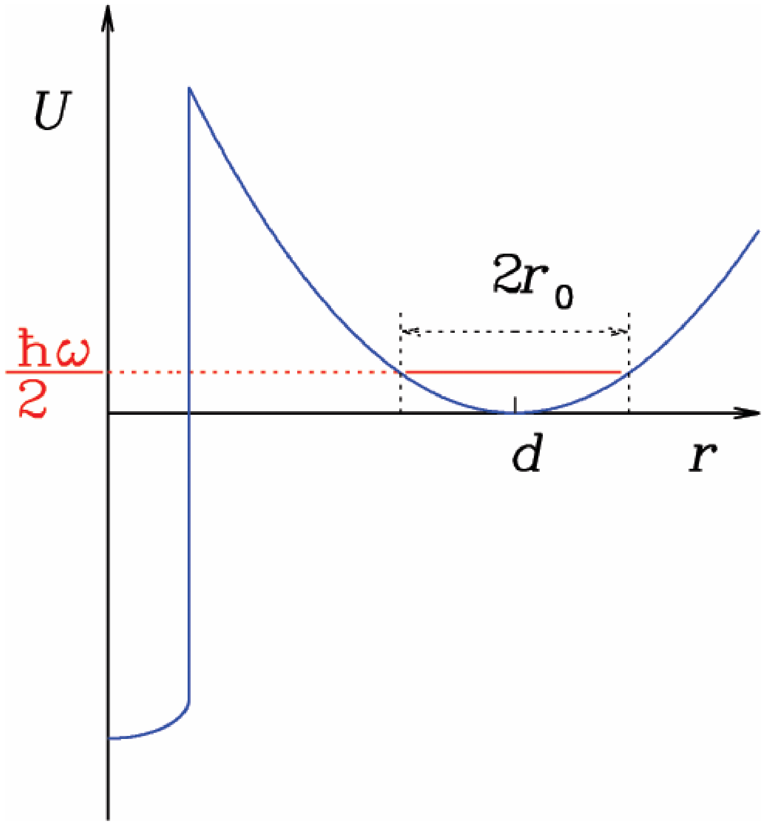
WKB tunneling:

$$\sigma(E) = \frac{S(E)P(E)}{E}, \qquad P(E) = \exp(-\eta)$$

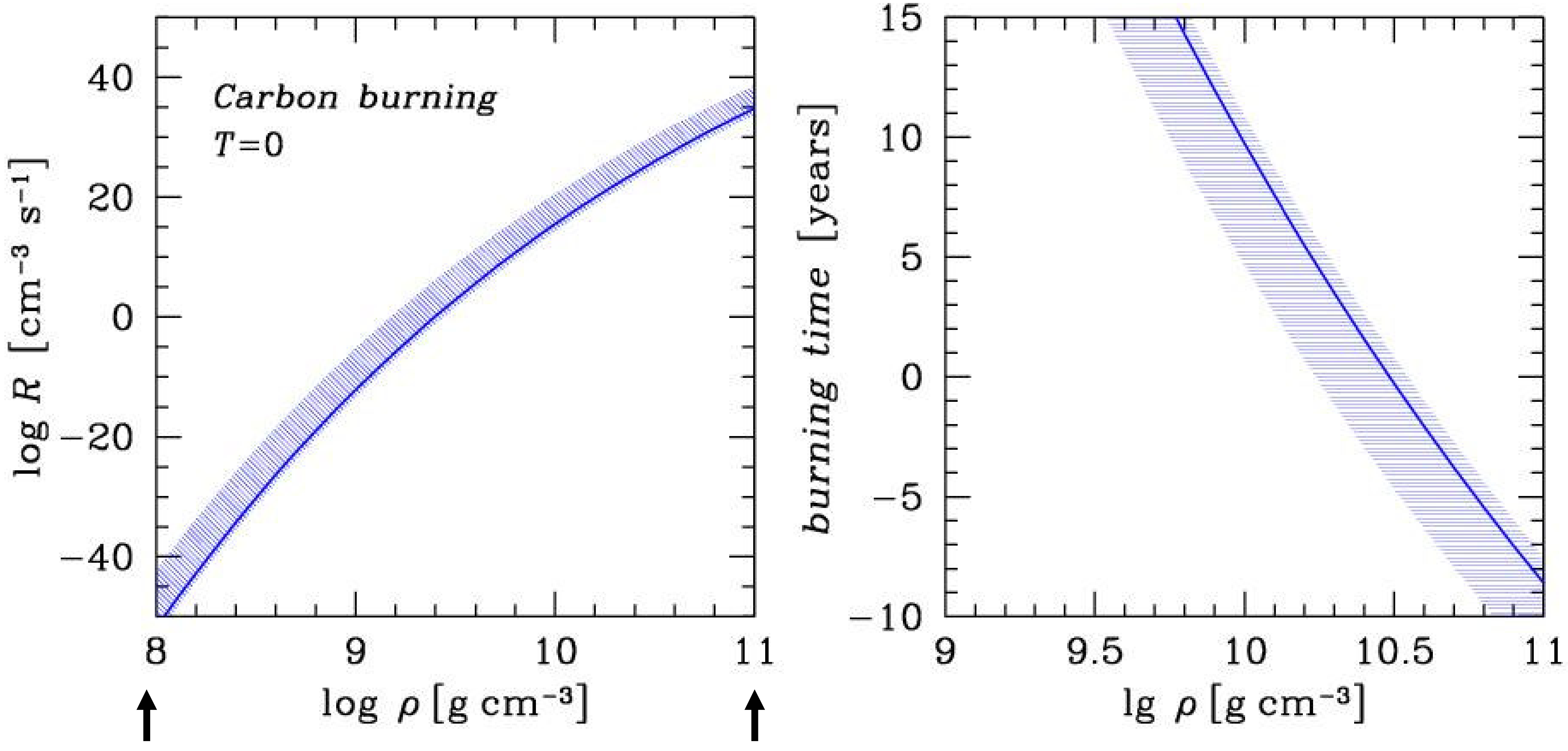
$$\eta(E) = \frac{2}{\hbar}\int_b^a \mathrm{d}r \;\; |p(r)| = \alpha\left(\frac{d}{r_0}\right)^2 \propto \frac{1}{\rho^{1/6}}$$

$$\alpha \sim 1 = ?$$

The reaction rate exponentially increases with growing density!



PYCNONUCLEAR BURNING OF DENSE STELLAR MATTER



t_{burn}~10^{75} yrs

t_{burn}~0.1 s

Gamow and Wildhack

APRIL 15, 1939 PHYSICAL REVIEW VOLUME 55

Physical Possibilities of Stellar Evolution

G. GAMOW
George Washington University, Washington, D. C.
(Received November 18, 1938)

The evolution of gaseous bodies, caused by different physical processes happening in their interior and serving as energy sources, is considered qualitatively and partially quantitatively in view of possible applications for the explanation of various observed states of known stars. It is shown that the part of evolution during which the main source of energy is given by *thermonuclear reactions* leads to a steadily increasing luminosity and goes over continuously into the *contractive stage* where the energy liberation is purely gravitational. The later stages of contraction and the transition into the state of *degenerate gas model* are discussed, in application to the present state of white dwarfs. Some remarks are made about the possibility of *neutron-core formation* in heavier stars, in application to the explosion phenomena observed in supernovae. An attempt is made to explain the energy production in *red giants* as due to thermonuclear reactions of *light elements* (lithium, beryllium, and boron), and the pulsation phenomena observed for *Cepheid variables* is interpreted as due to instability during the transitions from the giant branch into the main sequence.

JANUARY 15, 1940 PHYSICAL REVIEW VOLUME 57

The Proton-Deuteron Transformation As a Source of Energy in Dense Stars*

W. A. WILDHACK
George Washington University, Washington, D. C.
(Received November 4, 1938)

The rates of energy evolution due to the transformation to helium, starting with the reaction $H+H=D+e^+$, in hydrogen at densities of 10^4 to 10^8 g/cm^3, were calculated on the basis of complete degeneracy, and the assumption of a crystal-like spacing of the protons. The results indicate that any considerable amount of hydrogen in white dwarf stars would lead to much higher luminosities than those observed. Thus the low effective molecular weight (1.5) as calculated for some of these stars from the accepted white dwarf model, cannot be due to a high content of hydrogen. It might be explained as due to very large content (~100 percent) of the helium isotope He^3 but it is very difficult to see how such large amounts of this isotope could be present in these stars. It appears that the paradox can be removed only by revision of the observational data concerning the white dwarf radii.

Later History

Т. 33. Журнал экспериментальной и теоретической физики. Вып. 4 (10)

1957

О ЯДЕРНЫХ РЕАКЦИЯХ В СВЕРХПЛОТНОМ ХОЛОДНОМ ВОДОРОДЕ

Я. Б. Зельдович

Показано, что ядерные реакции, происходящие подбарьерно в холодном водороде при плотностях 10^4—10^6 *г/см*^{3}, идут с вполне заметной для астрофизических масштабов вероятностью. Это обстоятельство кладет предел возможному сжатию холодного водорода, так как уже при плотности $0{,}7 \cdot 10^5$ *г/см*^{3} небесное тело не может прожить более 10^8 лет. Такая плотность в холодном водороде достигается под действием гравитации при массе, близкой к массе Солнца.

Известно [1-3], что в звездах осуществляются термоядерные реакции $p + p = D + e^+ + \tilde{\nu}$, $p + D = He^3 + \gamma$ и далее при высокой температуре $He^3 + He^3 = He^4 + p + p$, а при высокой плотности $He^3 + e^- = T + \nu$, $T + p = He^4 + \gamma$.

Впервые Шатцман [4] отметил, что при высокой плотности и низкой тем-

- **Zel'dovich (1957)**
- **Cameron (1959) – "pycnos"**
- **Kirzhnits (1960)**
- **Kopyshev (1964)**
- **Wolf (1965)**
- **Van Horn (1966)**
- **Salpeter & Van Horn (1969)**
- **Schramm & Koonin (1990)**
- **Ichimaru, Ogata, Iyetomi, Kitamura, Van Horn**

Cold Fusion Experiments (March 1989)

Cold Fusion Research

November 1989

A Report of the Energy Research Advisory Board to the United States Department of Energy

Washington, DC 20585

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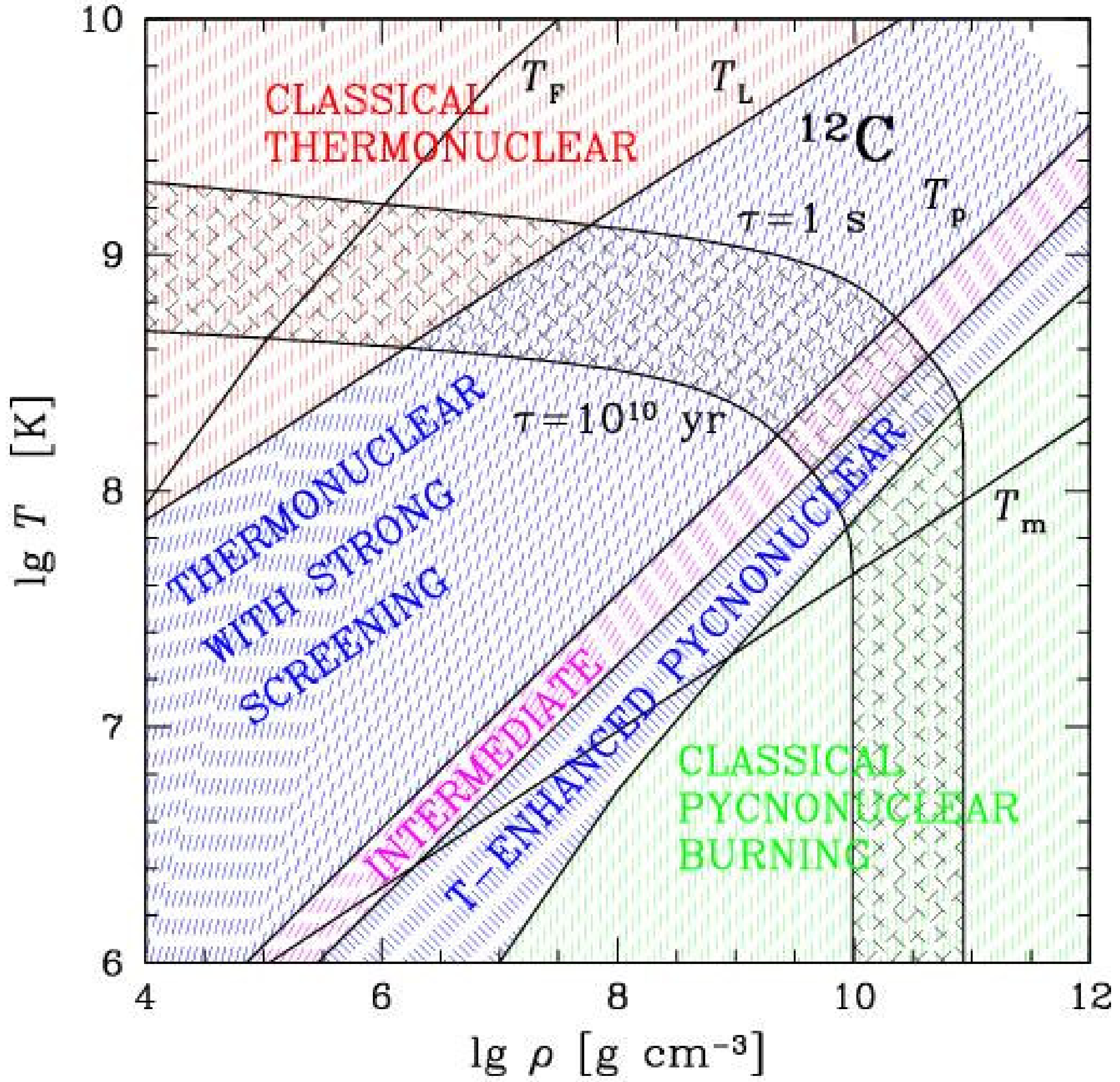
NCAS Introduction CONTENTS

The recent interest in cold fusion was stimulated by reports from Utah scientists in March 1989 that fusion had occurred in experiments on the electrolysis of heavy water (D_2O). Dr. Stanley Pons and Dr. Martin Fleischmann at the University of Utah claimed to measure a production of heat that could only be explained by a nuclear process. Dr. Steven Jones at Brigham Young University did not observe heat but claimed to observe neutron emission that would also indicate a nuclear process. The claims were particularly astounding given the simplicity of the equipment, just a pair of electrodes connected to a battery and immersed in a jar of D_2O--equipment easily available in many laboratories.

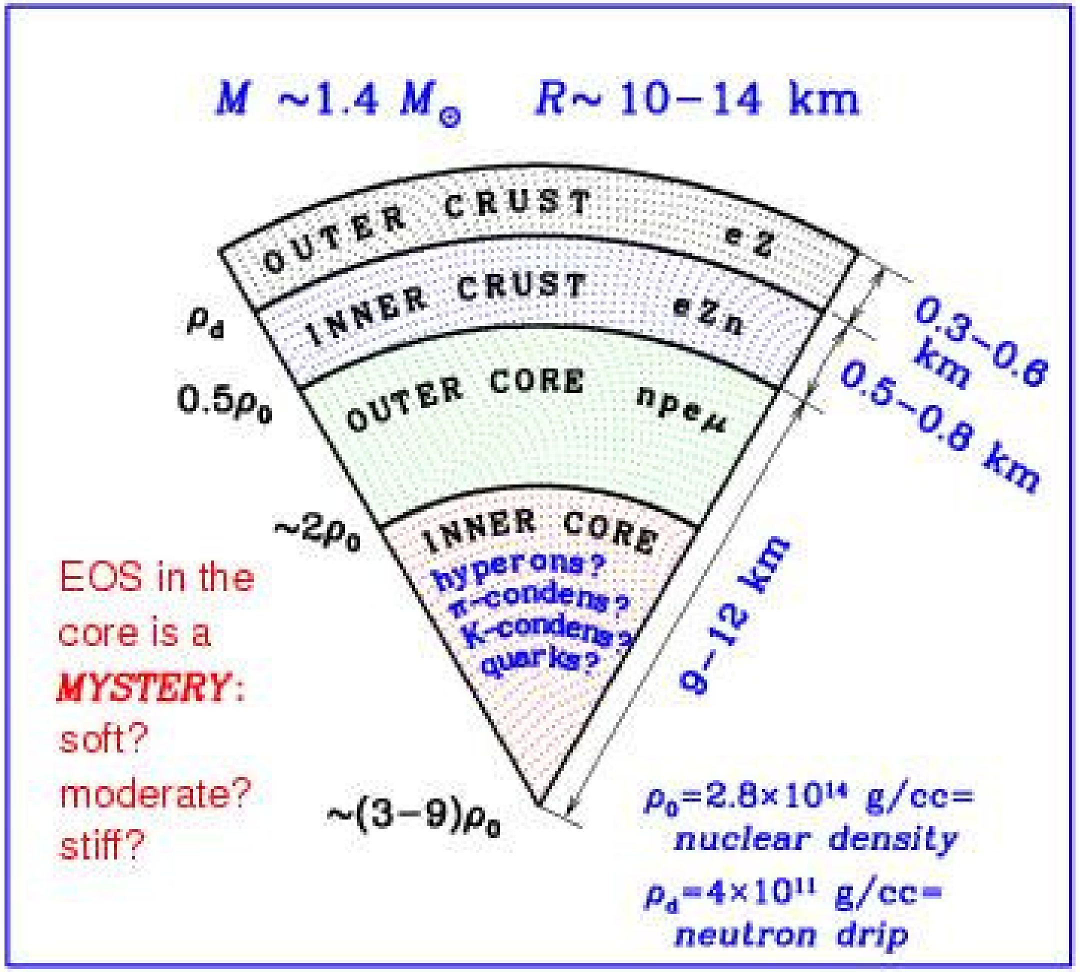
This was not the first time fusion had been claimed to occur in electrolysis experiments, the earliest dating to the late 1920's in experiments that were later retracted, as discussed below. Nonetheless the implications of the Utah claims, if they were correct, and the ready availability of the required equipment, led scientists around the world to attempt to repeat the experiments within hours of the announcement. The Panel estimates that several tens of millions of dollars have been spent in the United States on cold fusion experiments. These experiments are discussed in the following sections.

GENERAL OUTLOOK



Conditions for pycnonuclear burning:
(1) Light nuclei
(2) High densities
(3) Low temperatures

OVERALL STRUCTURE OF A NEUTRON STAR



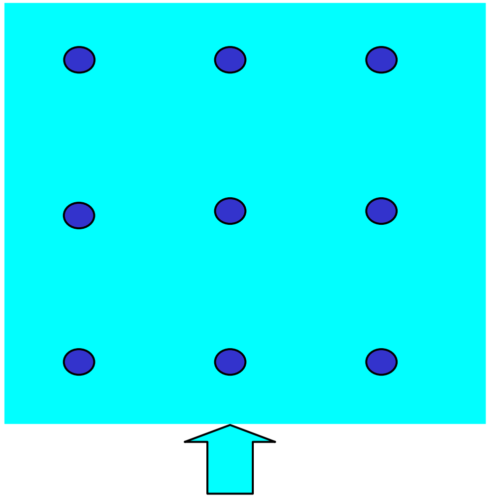
Four main layers:

1. Outer crust
2. Inner crust
3. Outer core
4. Inner core

The main mystery:

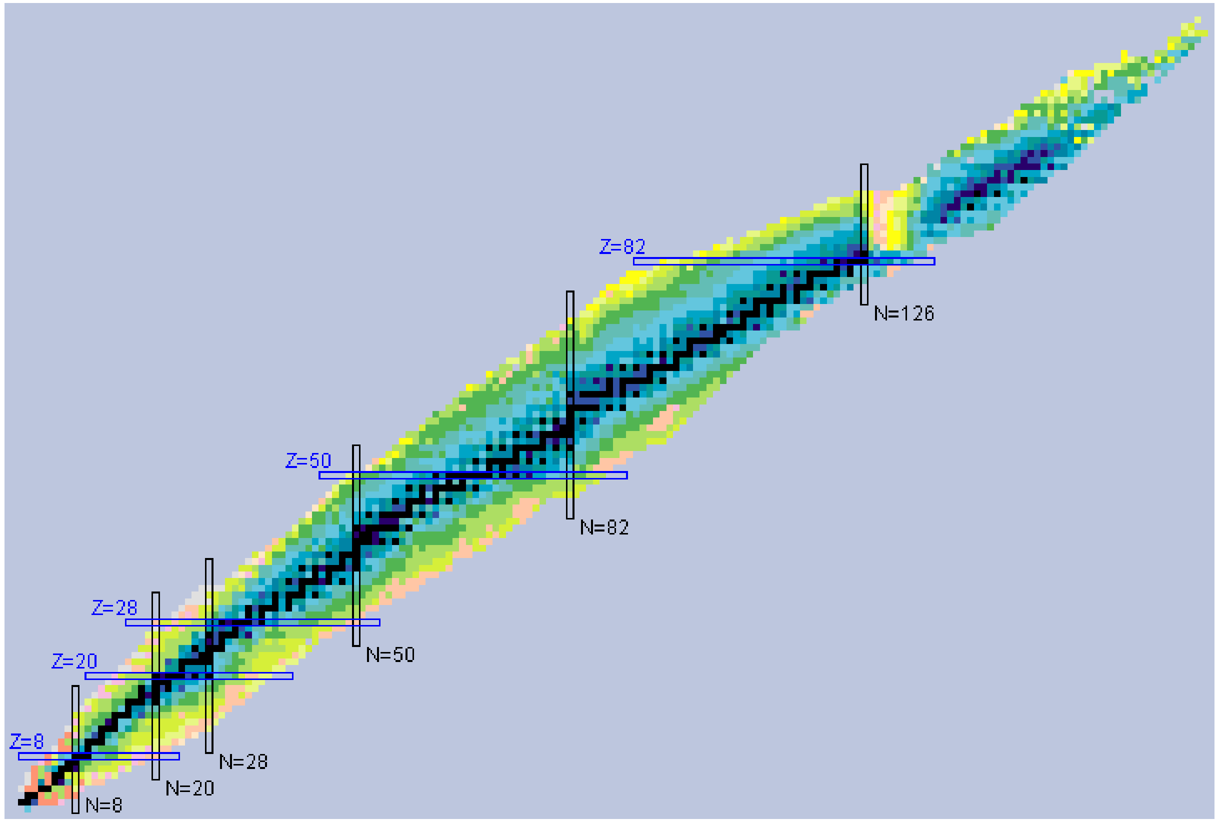
1. ***Composition of the core+***
2. ***The pressure of dense matter=***

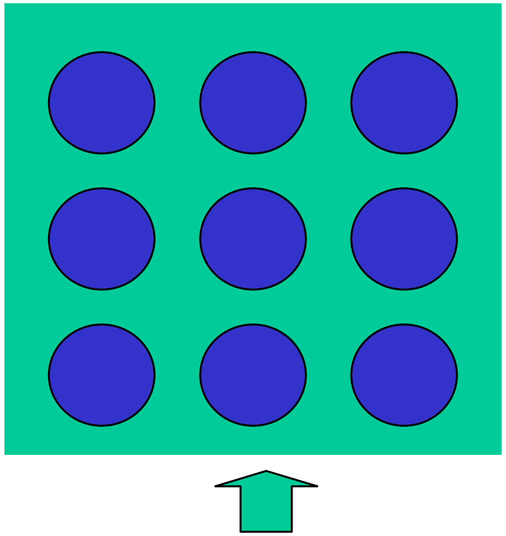
The problem of equation of state (EOS)



Electron background

OUTER CRUST $(\rho < 4\times10^{11}\ \ \mathrm{g/cm^3})$





e+n background

INNER CRUST $(4\times10^{11}\ \ \mathrm{g/cc}\ < \rho < \rho_0 / 2)$

Ground-state matter in the outer crust

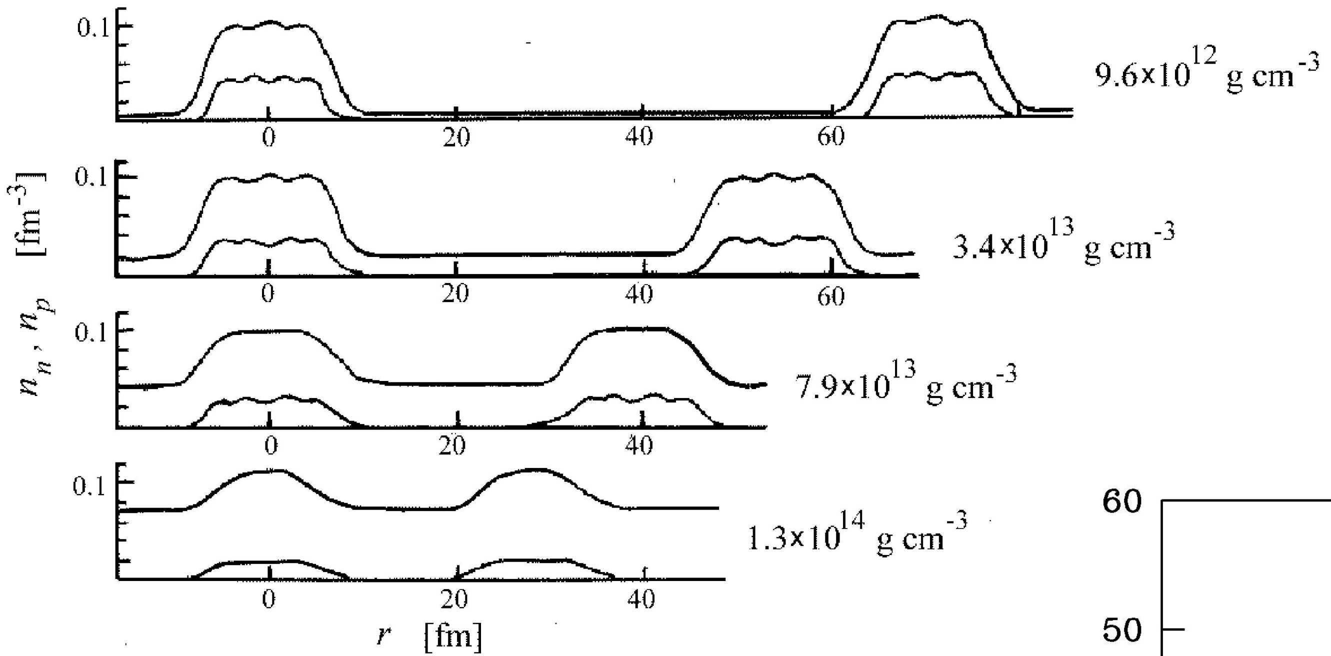
Baym, Pethick, Sutherland (1971)
Haensel, Pichon (1994)

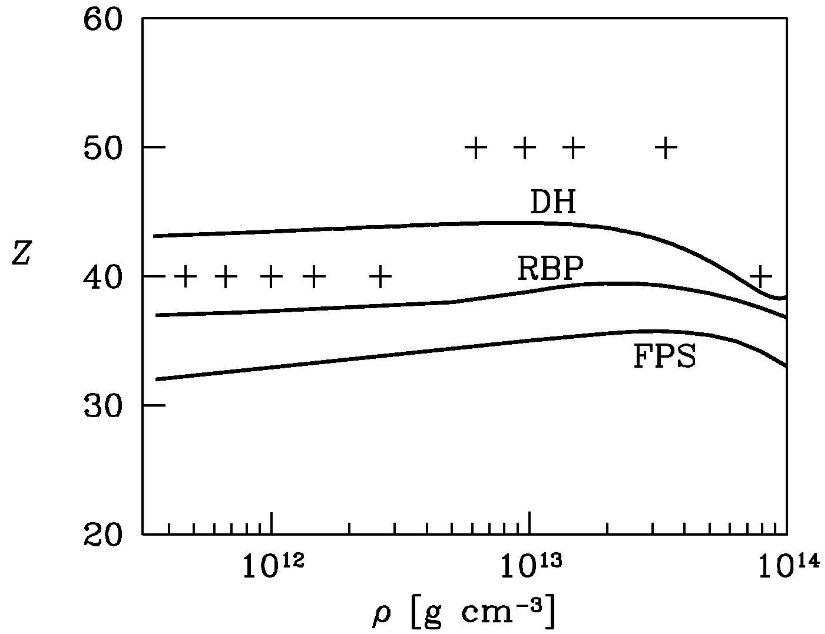
BPS71 →

In laboratory N=48 →

element	Z	N	Z/A	ρ_{max} (g cm^{-3})	μ_e (MeV)	$\Delta\rho/\rho$ (%)
^{56}Fe	26	30	0.4643	7.96×10^6	0.95	2.9
^{62}Ni	28	34	0.4516	2.71×10^8	2.61	3.1
^{64}Ni	28	36	0.4375	1.30×10^9	4.31	3.1
^{66}Ni	28	38	0.4242	1.48×10^9	4.45	2.0
^{86}Kr	36	50	0.4186	3.12×10^9	5.66	3.3
^{84}Se	34	50	0.4048	1.10×10^{10}	8.49	3.6
^{82}Ge	32	50	0.3902	2.80×10^{10}	11.4	3.9
^{80}Zn	30	50	0.3750	5.44×10^{10}	14.1	4.3
^{78}Ni	28	50	0.3590	9.64×10^{10}	16.8	4.0
^{126}Ru	44	82	0.3492	1.29×10^{11}	18.3	3.0
^{124}Mo	42	82	0.3387	1.88×10^{11}	20.6	3.2
^{122}Zr	40	82	0.3279	2.67×10^{11}	22.9	3.4
^{120}Sr	38	82	0.3167	3.79×10^{11}	25.4	3.6
^{118}Kr	36	82	0.3051	(4.32×10^{11})	(26.2)	

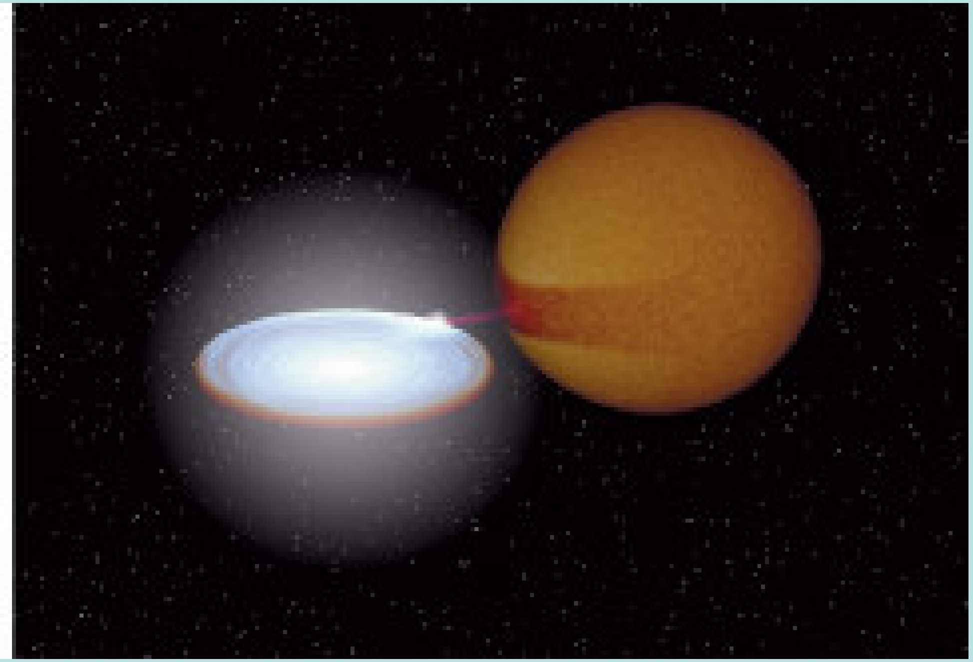
Ground-state matter in the inner crust





Negele & Vautherin (1973)

Soft X-ray transients



Active states: $L_X = 10^{36} - 10^{39}$ erg/s

weeks – months – years; X-ray bursts

Quiescent states: $L_X = 10^{30} - 10^{34}$ ergs/s

years - decades

SXRTs belong to LMXRBs

SXRT = neutron star + donor star

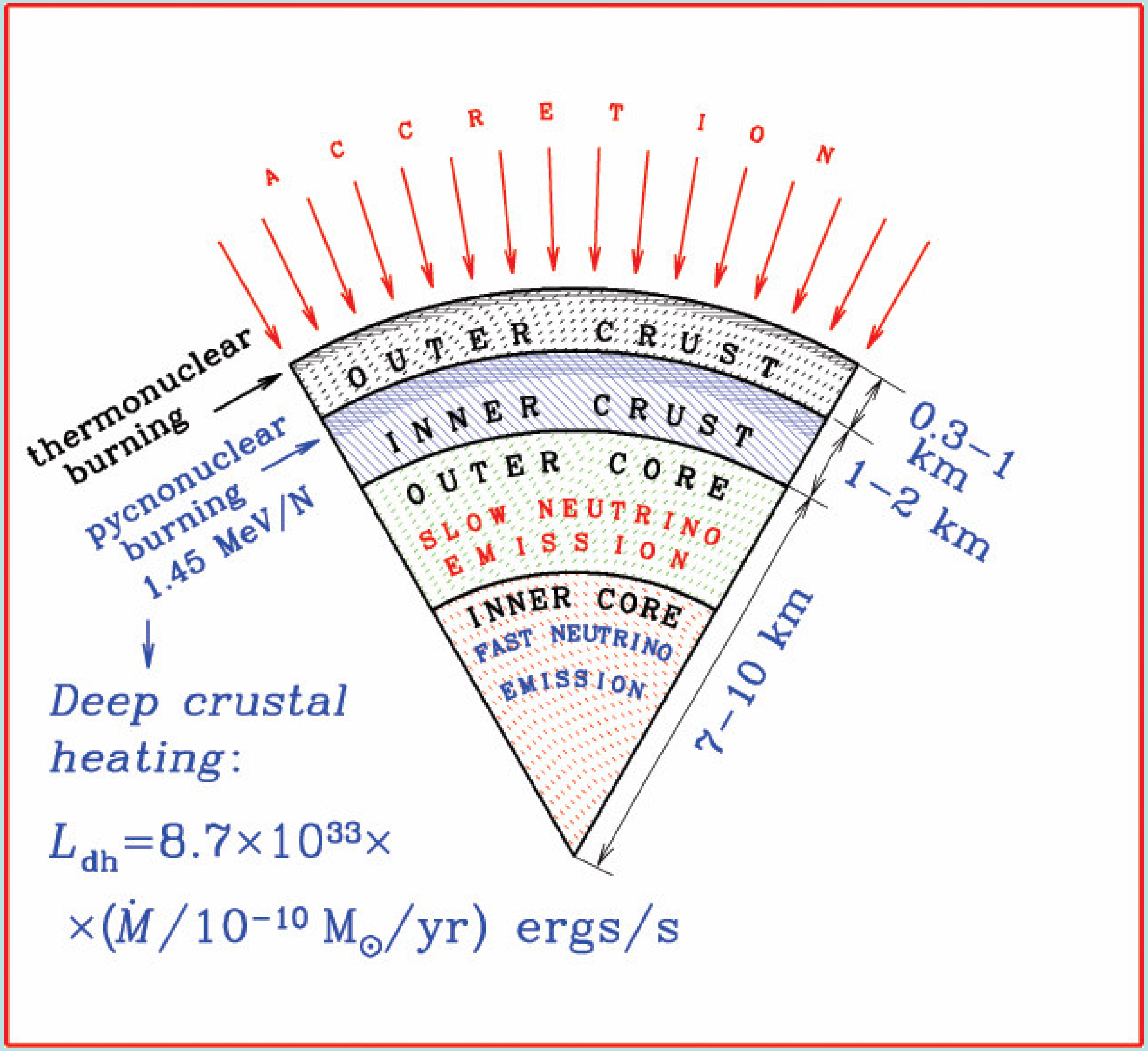
Donor star: main-sequence or
subgiant, $M \leq M_\odot$

P_{orb}: a few hours – a few days

$\langle \dot{M} \rangle \approx 10^{-11} - 10^{-9}\ M_\odot$/yr

Brown, Bildsten & Rutledge (1998):
Aql X-1 $T_s \sim 10^6$ K

Accreted Crust



Reactions:

1. **Beta captures**
2. **Neutron emission and absorption**
3. **Pycnonuclear reactions**

Work:

Haensel & Zdunik (1990)
Outer and inner crust
Starting from ^{56}Fe

Haensel & Zdunik (2003)
Outer and inner crust
Starting from ^{106}Pd

Gupta et al. (2006)
Outer crust starting either from rp-process ashes or from superburst ashes

Accreted crust: Starting from ^{56}Fe

Haensel and Zdunik 1990

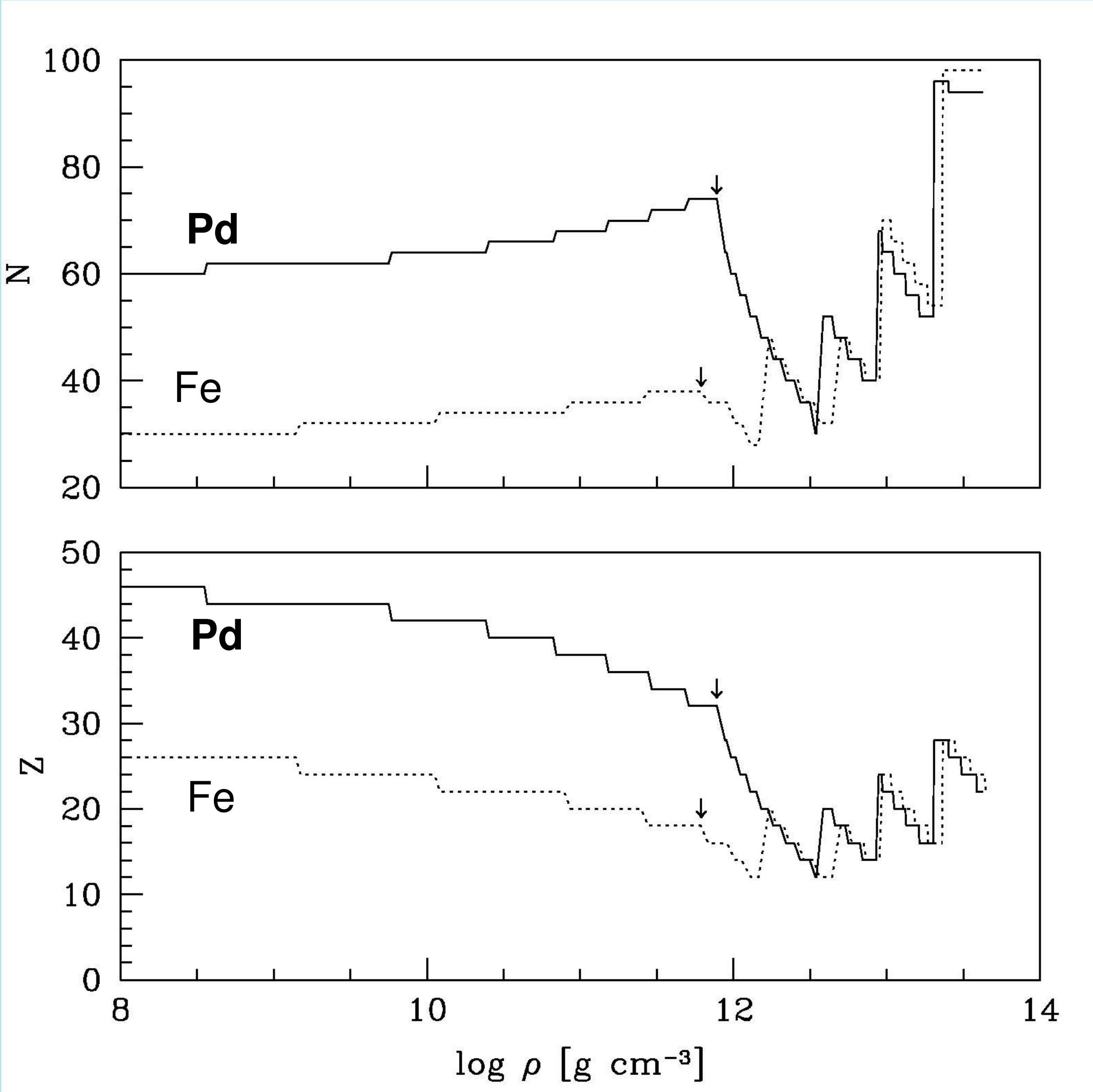
P (dyn cm^{-2})	ρ (g cm^{-3})	Process	$\Delta\rho/\rho$	q_{tot} (MeV)	q (MeV)
7.23×10^{26}	1.49×10^{9}	$^{56}Fe \rightarrow ^{56}Cr - 2e^- + 2\nu_e$	0.08	0.04	0.01
9.57×10^{27}	1.11×10^{10}	$^{56}Cr \rightarrow ^{56}Ti - 2e^- + 2\nu_e$	0.09	0.04	0.01
1.15×10^{29}	7.85×10^{10}	$^{56}Ti \rightarrow ^{56}Ca - 2e^- + 2\nu_e$	0.10	0.05	0.01
4.78×10^{29}	2.50×10^{11}	$^{56}Ca \rightarrow ^{56}Ar - 2e^- + 2\nu_e$	0.11	0.05	0.01
1.36×10^{30}	6.11×10^{11}	$^{56}Ar \rightarrow ^{52}S + 4n - 2e^- + 2\nu_e$	0.12	0.06	0.05
1.980×10^{30}	9.075×10^{11}	$^{52}S \rightarrow ^{46}Si + 6n - 2e^- + 2\nu_e$	0.07	0.13	0.09
2.253×10^{30}	1.131×10^{12}	$^{46}Si \rightarrow ^{40}Mg + 6n - 2e^- + 2\nu_e$	0.18	0.14	0.10
2.637×10^{30}	1.455×10^{12}	$^{40}Mg \rightarrow ^{34}Ne + 6n - 2e^- + 2\nu_e$	0.39	0.16	0.12
3.204×10^{30}	1.951×10^{12}	$^{34}Ne + ^{34}Ne \rightarrow ^{68}Ca$			
		$^{68}Ca \rightarrow ^{62}Ar + 6n - 2e^- + 2\nu_e$	0.39	0.09	0.40
3.216×10^{30}	2.134×10^{12}	$^{62}Ar \rightarrow ^{56}S + 6n - 2e^- + 2\nu_e$	0.45	0.09	0.05
3.825×10^{30}	2.634×10^{12}	$^{56}S \rightarrow ^{50}Si + 6n - 2e^- + 2\nu_e$	0.50	0.09	0.06
4.699×10^{30}	3.338×10^{12}	$^{50}Si \rightarrow ^{44}Mg + 6n - 2e^- + 2\nu_e$	0.55	0.09	0.07
6.043×10^{30}	4.379×10^{12}	$^{44}Mg \rightarrow ^{36}Ne + 8n - 2e^- + 2\nu_e$			
		$^{36}Ne + ^{36}Ne \rightarrow ^{72}Ca$			
		$^{72}Ca \rightarrow ^{66}Ar + 6n - 2e^- + 2\nu_e$	0.61	0.14	0.28
7.233×10^{30}	5.839×10^{12}	$^{66}Ar \rightarrow ^{60}S + 6n - 2e^- + 2\nu_e$	0.70	0.04	0.02
9.238×10^{30}	7.041×10^{12}	$^{60}S \rightarrow ^{54}Si + 6n - 2e^- + 2\nu_e$	0.73	0.04	0.02
1.228×10^{31}	8.980×10^{12}	$^{54}Si \rightarrow ^{48}Mg + 6n - 2e^- + 2\nu_e$	0.76	0.04	0.03
1.602×10^{31}	1.127×10^{13}	$^{48}Mg + ^{48}Mg \rightarrow ^{96}Cr$	0.79	0.004	0.11
1.613×10^{31}	1.137×10^{13}	$^{96}Cr \rightarrow ^{88}Ti + 8n - 2e^- + 2\nu_e$	0.80	0.02	0.01

Accreted crust: Starting from ^{106}Pd

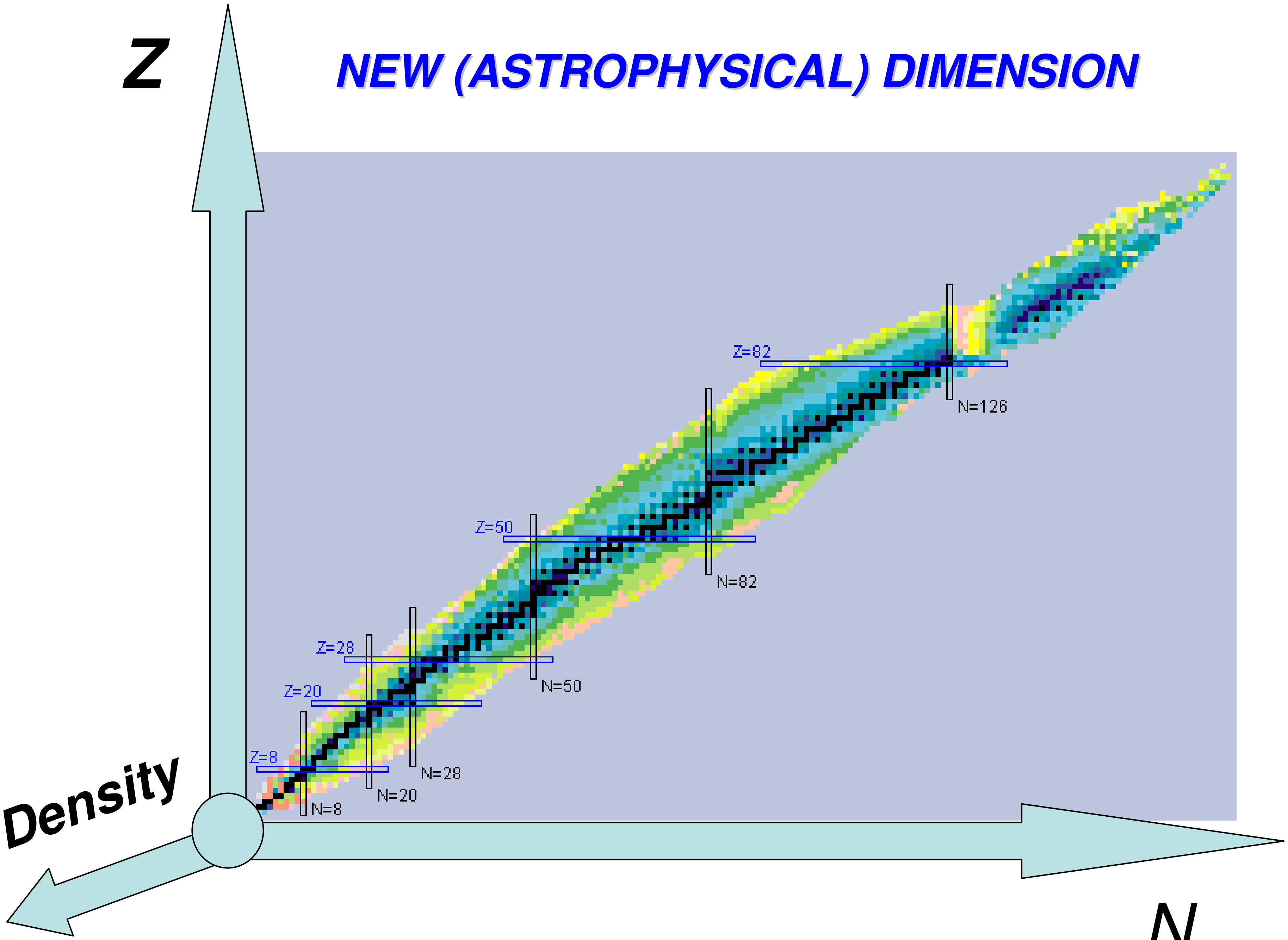
Haensel and Zdunik 2003

P (dyn cm^{-2})	ρ (g cm^{-3})	reactions	X_n	$\Delta\rho/\rho$ %	q (keV)
9.235×10^{25}	3.517×10^{08}	^{106}Pd $\rightarrow^{106}$ Ru $- 2e^- + 2\nu_e$	0	4.4	5.7
3.603×10^{27}	5.621×10^{09}	^{106}Ru $\rightarrow^{106}$ Mo $- 2e^- + 2\nu_e$	0	4.6	5.7
2.372×10^{28}	2.413×10^{10}	^{106}Mo $\rightarrow^{106}$ Zr $- 2e^- + 2\nu_e$	0	4.9	5.6
8.581×10^{28}	6.639×10^{10}	^{106}Zr $\rightarrow^{106}$ Sr $- 2e^- + 2\nu_e$	0	5.1	5.6
2.283×10^{29}	1.455×10^{11}	^{106}Sr $\rightarrow^{106}$ Kr $- 2e^- + 2\nu_e$	0	5.4	5.5
5.025×10^{29}	2.774×10^{11}	^{106}Kr $\rightarrow^{106}$ Se $- 2e^- + 2\nu_e$	0	5.7	5.5
9.713×10^{29}	4.811×10^{11}	^{106}Se $\rightarrow^{106}$ Ge $- 2e^- + 2\nu_e$	0	6.1	5.5
1.703×10^{30}	7.785×10^{11}	^{106}Ge $\rightarrow^{92}$ Ni $+ 14n - 4e^- + 4\nu_e$	0.13	13.2	77.6
1.748×10^{30}	8.989×10^{11}	^{92}Ni $\rightarrow^{86}$ Fe $+ 6n - 2e^- + 2\nu_e$	0.19	6.9	39.2
1.924×10^{30}	1.032×10^{12}	^{86}Fe $\rightarrow^{80}$ Cr $+ 6n - 2e^- + 2\nu_e$	0.25	7.3	43.1
2.135×10^{30}	1.197×10^{12}	^{80}Cr $\rightarrow^{74}$ Ti $+ 6n - 2e^- + 2\nu_e$	0.30	7.7	47.4
2.394×10^{30}	1.403×10^{12}	^{74}Ti $\rightarrow^{68}$ Ca $+ 6n - 2e^- + 2\nu_e$	0.36	8.1	52.3
2.720×10^{30}	1.668×10^{12}	^{68}Ca $\rightarrow^{62}$ Ar $+ 6n - 2e^- + 2\nu_e$	0.42	8.5	57.7
3.145×10^{30}	2.016×10^{12}	^{62}Ar $\rightarrow^{56}$ S $+ 6n - 2e^- + 2\nu_e$	0.47	9.0	63.7
3.723×10^{30}	2.488×10^{12}	^{56}S $\rightarrow^{50}$ Si $+ 6n - 2e^- + 2\nu_e$	0.53	9.4	70.5
4.549×10^{30}	3.153×10^{12}	^{50}Si $\rightarrow^{42}$ Mg $+ 8n - 2e^- + 2\nu_e$	0.61	8.8	79.0
4.624×10^{30}	3.472×10^{12}	^{42}Mg $\rightarrow^{36}$ Ne $+ 6n - 2e^- + 2\nu_e$			
		^{36}Ne $+^{36}$ Ne $\rightarrow^{72}$ Ca	0.66	10.6	251.8
5.584×10^{30}	4.399×10^{12}	^{72}Ca $\rightarrow^{66}$ Ar $+ 6n - 2e^- + 2\nu_e$	0.69	4.8	25.3
6.883×10^{30}	5.355×10^{12}	^{66}Ar $\rightarrow^{60}$ S $+ 6n - 2e^- + 2\nu_e$	0.72	4.7	27.3
8.749×10^{30}	6.655×10^{12}	^{60}S $\rightarrow^{54}$ Si $+ 6n - 2e^- + 2\nu_e$	0.75	4.6	29.2
1.157×10^{31}	8.487×10^{12}	^{54}Si $\rightarrow^{46}$ Mg $+ 8n - 2e^- + 2\nu_e$			
		^{46}Mg $+^{46}$ Mg $\rightarrow^{92}$ Cr	0.79	4.0	139.6
1.234×10^{31}	9.242×10^{12}	^{92}Cr $\rightarrow^{86}$ Ti $+ 6n - 2e^- + 2\nu_e$	0.80	2.0	8.9
1.528×10^{31}	1.096×10^{13}	^{86}Ti $\rightarrow^{80}$ Ca $+ 6n - 2e^- + 2\nu_e$	0.82	1.9	9.0
1.933×10^{31}	1.317×10^{13}	^{80}Ca $\rightarrow^{74}$ Ar $+ 6n - 2e^- + 2\nu_e$	0.83	1.8	8.8
2.510×10^{31}	1.609×10^{13}	^{74}Ar $\rightarrow^{68}$ S $+ 6n - 2e^- + 2\nu_e$	0.85	1.7	10.2
3.363×10^{31}	2.003×10^{13}	^{68}S $\rightarrow^{62}$ Si $+ 6n - 2e^- + 2\nu_e$			
		^{62}Si $+^{62}$ Si $\rightarrow^{124}$ Ni	0.86	1.7	70.3
4.588×10^{31}	2.520×10^{13}	^{124}Ni $\rightarrow^{120}$ Fe $+ 4n - 2e^- + 2\nu_e$	0.87	0.8	2.6
5.994×10^{31}	3.044×10^{13}	^{120}Fe $\rightarrow^{118}$ Cr $+ 2n - 2e^- + 2\nu_e$	0.88	0.9	2.4
8.408×10^{31}	3.844×10^{13}	^{118}Cr $\rightarrow^{116}$ Ti $+ 2n - 2e^- + 2\nu_e$	0.88	0.8	2.2

Starting from ^{56}Fe or ^{106}Pd?



NEW (ASTROPHYSICAL) DIMENSION



SUMMARY

1. Cold dense matter undergoes pycnonuclear burning
2. Pycnonuclear burning is inefficient in ordinary stars but can be important in cores of white dwarfs and envelopes of neutron stars
3. Applications of pycnonuclear burning include:

   (a) explosion of white dwarfs as supernovae Ia

   (b) deep crustal heating of transiently accreting neutron stars
4. The theory of pycnonuclear burning is far from perfect
5. There is a wide field for nuclear physicists in the physics of neutron stars