Strangeness Condensation and Neutron Stars

2005 Summer Workshop Experimental Hall C

Jefferson Lab

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Neutron Stars

- produced in supernova explosions (type II)
- compact, massive objects: radius $\approx 10$ km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 3 \cdot 10^{14}$ g/cm$^3$
Masses of Pulsars (Thorsett and Chakrabarty (1999))

- more than 1500 pulsars known
- best determined mass: $M = (1.4411 \pm 0.00035)M_\odot$ (Hulse-Taylor-Pulsar)
- shortest rotation period: 1.557 ms (PSR 1937+21)
Heavy Neutron Stars in Pulsar–White Dwarfs Systems?

(Nice, Splaver, Stairs (2003))

- four pulsars with a white dwarf companion
- measure masses by changes in the pulsar signal
- shaded area: from theoretical limits for white–dwarf companion
- massive pulsar J0751+1807: \( M = 1.6 - 2.8M_\odot \) (2\( \sigma \!\!\!\!\)!) 
- Nice et al. (2005): 
  \[ M = 2.1 \pm 0.2M_\odot \] (1\( \sigma \!\!\!\!\)!) and 
  \[ M = 1.6 - 2.5M_\odot \] (2\( \sigma \!\!\!\!\)!!)
spin rate from PSR B1937+21 of 641 Hz: $R < 15.5$ km for $M = 1.4M_\odot$

observed giant glitch from Vela pulsar: moment of inertia changes by 1.4

Schwarzschild limit (GR): $R > 2GM = R_s$

causality limit for EoS: $R > 3GM$
Isolated Neutron Star RX J1856

- closest known neutron star
- perfect black–body spectrum, no spectral lines!
- for black-body emission: $T = 60$ eV and $R_{\infty} = R \sqrt{1 - \frac{2GM}{R}} = 4 - 8$ km!

NASA news release 02-082:
“Cosmic X-rays reveal evidence for new form of matter”
— a quark star?
- H atmospheres ruled out, they over-predict the optical flux!
- heavy element atmospheres ruled out, as there are no spectral lines!
- all classic neutron star atmosphere models fail!
- alternatives: two-component blackbody model (left plot)
- or condensed matter surface for low $T < 86$ eV and high $B > 10^{13}$ G (right plot) — grey body with a suppression of a factor 7!
- two-component blackbody: small soft temperature, so as not to spoil the x-ray band
- this implies a rather LARGE radius so that the optical flux is right!
- conservative lower limit: $R_\infty = 16.5 \text{ km (d}/117 \text{ pc})$
- excludes quark stars and even neutron stars with a quark core!
Supernova remnant 3C58 from 1181 AD (Slane et al. 2004)

CHANDRA press release 04-13:
“Going to Extremes: Pulsar Gives Insight on Ultra Dense Matter and Magnetic Fields” — rapid cooling due to unexpected conditions in the neutron star!
newest data from four neutron stars suggest fast cooling (direct URCA)
standard cooling curves are too high!
large nuclear asymmetry energy generates fast cooling!
strange particles (exotic matter) generate fast cooling!
X-Ray burster \cite{CottamPaerelsMendez2002}

- binary systems of a neutron star with an ordinary star
- accreting material on the neutron star ignites nuclear burning
- explosion on the surface of the neutron star: x-ray burst
- red shifted spectral lines measured! ($z = 0.35 \rightarrow \frac{M}{M_\odot} = 1.5 \ (R/10 \ km)$)

movie
Modelling the Neutron Star Crust
\[ n \leq 10^4 \text{ g/cm}^3: \]

atmosphere (atoms)
Structure of Neutron Stars — the Crust (Dany Page)

- $n \leq 10^4 \text{ g/cm}^3$: atmosphere (atoms)
- $n = 10^4 - 4 \cdot 10^{11} \text{ g/cm}^3$: outer crust or envelope (free $e^-$, lattice of nuclei)
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- $n = 10^4 - 4 \cdot 10^{11} \text{ g/cm}^3$: outer crust or envelope (free $e^-$, lattice of nuclei)
- $n = 4 \cdot 10^{11} - 10^{14} \text{ g/cm}^3$: Inner crust (lattice of nuclei with free neutrons and $e^-$)
Composition of the crust of a neutron star

lattice of nuclei surrounded by free electrons

- Wigner–Seitz–cell, lattice structure is bcc
- minimize \( E = E_{\text{nuclei}} + E_{\text{lattice}} + E_{\text{electrons}} \)
- loop over all particle stable nuclei (up to 14.000)
- use atomic mass evaluation of 2003 by Audi, Wapstra, and Thibault
- extrapolate to the drip–line with various models
- \( \rightarrow \) sequence of nuclei \( {}^A Z \) as a function of density
Nuclear Models

- **Nonrelativistic nuclear models:**
  - Skyrme Hartree-Fock plus BCS pairing (MSk7)
  - Skyrme Hartree-Fock-Bogoliubov (SLy4, SkP, SkM*, BSk8)
  - Extended Thomas-Fermi models plus BCS pairing (SkSC4, SkSC18)

- **Relativistic nuclear models:**
  - Relativistic Mean–Field (NL3, NL-Z2)
  - Relativistic Point–Coupling (PCF1)
  - Chiral Effective Lagrangian (Chiral)

nuclear data tables generated “in-house” or taken from home-pages of BRUSLIB and Dobaczewski
Chiral Effective Lagrangian

(Papazoglou, Zschiesche, JSB, Schramm, Stöcker, Greiner, PRC 59, 411 (1999))

- invariant under $SU(3)_L \times SU(3)_R$ chiral symmetry
- with scalar + pseudoscalar, vector + axial-vector meson–nonet
- with baryon octet (and baryon decuplet)
- with explicit and spontaneous symmetry breaking
- fit to hadron masses, nuclei and hypernuclei ($\sim 10$ parameters)

good description of hadron masses, nuclear matter, nuclei and hypernuclei
outer crust starts with iron ($^{56}$Fe) up to $\rho \approx 10^7$ g/cm$^3$
continues along nickel isotopes ($Z = 28$), then Kr, Se ($N = 50$)
initial sequence at low densities independent of parameter set (data)!
equation of state (nearly) independent of parameter set!
sequence to the dripline ii (hempel, rüster, jsb 2005)

- selection of state-of-the-art mass tables (deformed calculations)
- initial sequence of nuclei: se, ge, zn (data)
- overall narrow range in \( Z \)
- neutron drip around \( 5 \cdot 10^{11} \) g/cm\(^3\)
Nuclei in the crust  (Hempel, Rüster, JSB 2005)

- sequence of nuclei: along $N = 50$ then along $N = 82$ with $Z = 46 - 34$
- common endpoint around $N = 82$ and $Z = 36$ (!)
- common location of the dripline at $N = 82$ (!)
- updates classic work of Baym, Pethick, Sutherland from 1971!
Modelling the Neutron Star Core
Structure of a Neutron Star — the Core

(Fridolin Weber)

**absolutely stable strange quark matter**

- \( M \approx 1.4 M_\odot \)
- \( R \approx 10 \text{ km} \)

- Quarks: \( u, d, s, \mu \)

- Neutron star with pion condensate

- Hyperon star

- Quark–hybrid star

- Nucleon star

- Traditional neutron star

- Strange star

**Fe**

- \( 10^6 \text{ g/cm}^3 \)
- \( 10^{11} \text{ g/cm}^3 \)
- \( 10^{14} \text{ g/cm}^3 \)
Neutron Star Matter for a Free Gas

(Ambartsumyan and Saakyan, 1960)

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but the corresponding equation of state results in a maximum mass of only $M_{\text{max}} < 1.44 M_\odot$ (Oppenheimer and Volkoff, 1939). Effects from strong interactions are essential to describe neutron stars!
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$\Rightarrow$ effects from strong interactions are essential to describe neutron stars!
NΛ: attractive $\rightarrow$ Λ-hypernuclei for $A = 3 - 209$

$U_\Lambda = -30$ MeV at $n = n_0$
Baryon–Baryon Interactions

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\( U_\Lambda = -30 \) MeV at \( n = n_0 \)

\( N\Sigma \): \( ^4\Sigma \)He hypernucleus bound by isospin forces
\( \Sigma^- \) atoms: potential is repulsive
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$N\Xi$: attractive $\rightarrow 7 \Xi$ hypernuclear events

$U_\Xi = -28$ MeV at $n = n_0$

quasi-free production of $\Xi$: $U_\Xi = -18$ MeV
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more attractive than $N\Lambda$?
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more attractive than $\Lambda\Lambda$?

$YY$: $Y = \Lambda, \Sigma, \Xi, \text{unknown!}$
Single–Particle Energies

\( A \) measured in \((\pi^+, K^+)\) reactions

• spin–orbit splitting smaller than experimental resolution

• fit to single particle energies: \( U_\Lambda = -27 \text{ MeV for } A \rightarrow \infty \)

(Rufa, JS, Maruhn, Stöcker, Greiner, Reinhard (1990))
• hyperon potential in various (relativistic) parameterizations
• hyperon potential becomes repulsive above $2n_0$
• compatible with hypernuclear data, three-body interactions for hyperons
  (MDG: Millener, Dover, Gal 1988)
two $\Lambda$s bound in a nucleus, produced by $\Xi^-$ capture

1963 Danysz et al.: $^{10}_{\Lambda\Lambda}\text{Be} \rightarrow ^9_{\Lambda}\text{Be} + p + \pi^-$

1966 Prowse: $^{6}_{\Lambda\Lambda}\text{He} \rightarrow ^5_{\Lambda}\text{He} + p + \pi^-$
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Hypernuclei

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2001 E373 (KEK): $^{\Lambda\Lambda}_6\text{He} \rightarrow ^5_{\Lambda}\text{He} + p + \pi^-$

2001 E906 (BNL): $^{\Lambda\Lambda}_4\text{He} \rightarrow ^4_{\Lambda}\text{He} + \pi^-$ \ ($\approx 400$ events!)
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- $\Lambda\Lambda$ interaction is attractive
Hypermolecules

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2001 E373 (KEK): $^{6}_{\Lambda\Lambda}\text{He} \rightarrow ^5_{\Lambda}\text{He} + p + \pi^-$

2001 E906 (BNL): $^{4}_{\Lambda\Lambda}\text{H} \rightarrow ^4_{\Lambda}\text{He} + \pi^-$ ($\approx 400$ events!)

- $\Lambda\Lambda$ interaction is attractive
- no strong decay to the H-dibaryon seen

$\Lambda + \Lambda \rightarrow H \leadsto m_H > 2m_\Lambda - B_{\Lambda\Lambda} \sim 2220$ MeV
Systems of Nucleons and Hyperons

- Pauli–blocking of the reactions: $\Lambda + \Lambda \leftrightarrow \Xi + N$, $Q \approx -25$ MeV
- $\Sigma$s are not stable: $\Sigma + N \rightarrow \Lambda + N$, $Q \approx -80$ MeV
- nuclear binding energy with $\Delta$s and $\Xi$s increases to $E/A = -12$ MeV!

(JS, Dover, Gal, Greiner, Stöcker (1993))
Neutron Star Matter and Hyperons

Hyperons appear at $n \approx 2n_0$!
(based on hypernuclear data!)

- nonrelativistic potential model (Balberg and Gal, 1997)
- quark-meson coupling model (Pal et al., 1999)
- relativistic mean–field models (Glendenning, 1985; Knorren, Prakash, Ellis, 1995; JS and Mishustin, 1996)
- Brueckner–Hartree–Fock (Baldo, Burgio, Schulze, 2000; Vidana et al., 2000)
- chiral effective Lagrangian’s (Hanauske et al., 2000)
- density-dependent hadron field theory (Hofmann, Keil, Lenske, 2001)

$\Rightarrow$ neutron stars are strange !!!
Impact of hyperons on the maximum mass of neutron stars

- neutron star with nucleons and leptons only:
  \[ M \approx 2.3M_{\odot} \]
- substantial decrease of the maximum mass due to hyperons!
- maximum mass for “giant hypernuclei”: \[ M \approx 1.7M_{\odot} \]
- noninteracting hyperons result in a too low mass: \[ M < 1.4M_{\odot} \]

(Glendenning and Moszkowski 1991)
Modern many-body approaches to neutron stars

beyond mean-field . . .

- Relativistic Hartree-Fock (Huber et al. 1998): 
  \[ M_{\text{max}} = 1.3 - 1.6 M_\odot \] depending on hyperon coupling strength

- Brueckner-Hartree-Fock: using Nijmegen soft-core YN potential

- Vidana et al. (2000): 
  \[ M_{\text{max}} = 1.47 M_\odot \] (NN and YN interactions),
  \[ M_{\text{max}} = 1.34 M_\odot \] (NN, NY, YY interactions)

- Baldo et al. (2000): 
  \[ M_{\text{max}} = 1.26 M_\odot \] including three-body forces

- too soft EoS, too low masses!

- three-body force for hyperons? momentum dependence?
  typically \( p = 300 - 600 \) MeV
• attractive potential for $\Sigma$s and $\Xi$s
• $\Sigma^-$ appear shortly before $\Lambda$s around $n = 2n_0$
• $\Lambda$s present in matter at $n = 2.5n_0$, $\Xi^-$ before $n = 3n_0$
\begin{itemize}
\item Λs are present close to \( n = 2n_0 \)
\item repulsive potential for Σs: Σ hyperons do not appear at all!
\item Ξ\(^{-}\) present in matter before \( n = 3n_0 \)
\end{itemize}
- increase strength of YY interactions
- first order phase transition, mixed phase for a wide range of densities
- all hyperons ($\Lambda$, $\Xi^0$, $\Xi^-$) appear at the start of the mixed phase
new stable solution in the mass–radius diagram!

neutron star twins:

\[ M_{\text{hyp}} \sim M_n \text{ but } R_{\text{hyp}} < R_n \]

selfbound compact stars for strong attraction with \( R = 7 - 8 \text{ km} \)

(JSB, Hanauske, Stöcker, Greiner, PRL 89, 171101 (2002))
third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!

generates stars more compact than neutron stars!

possible for any first order phase transition!
• delayed collapse of a proto-neutron star to a black hole (Thorsson, Prakash, Lattimer, 1994)
Signals for a Third Family/Phase Transition?

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- ...
Cooling processes with neutrinos

modified URCA process (slow):

\[ N + p + e^- \rightarrow N + n + \nu_e \quad N + n \rightarrow N + p + e^- + \bar{\nu}_e \]

direct URCA process (fast):

\[ p + e^- \rightarrow n + \nu_e \quad n \rightarrow p + e^- + \bar{\nu}_e \]

can only proceed for \( p_F^p + p_F^e \geq p_F^n \) ! Charge neutrality implies:

\[ n_p = n_e \quad \leftrightarrow \quad p_F^p = p_F^e \quad \leftrightarrow \quad 2p_F^p = p_F^n \quad \leftrightarrow \quad n_p/n \geq 1/9 \]

nucleon URCA only possible for a large fraction of protons!

hyperon URCA process:

\[ \Lambda \rightarrow p + e^- + \bar{\nu}_e \quad , \quad \Sigma^- \rightarrow n + e^- + \bar{\nu}_e \quad , \quad \ldots \]

happens immediately when hyperons are present!

only suppressed by hyperon pairing gaps!
Hyperon cooling with gaps (Schaab, JSB, Balberg 1998)

- slow cooling for low mass neutron stars
- fast cooling for heavier ones (direct nucleon URCA)
- hyperons are present in the core for \( M \geq 1.35M_\odot \)
- hyperon cooling suppressed by pairing gaps (same curve for \( M = 1.6M_\odot \))
- fast cooling for $M \geq 1.3M_\odot$ stars via direct nucleon URCA
- even faster cooling for heavier stars via hyperon direct URCA
- hyperon cooling not suppressed by pairing gaps!
- tiny density range of unpaired $\Lambda$ hyperons present as $\Sigma$ hyperons appear later!
Future of Pulsar Physics: Square Kilometer Array (SKA)

- receiving surface of 1 million square kilometers
- 1 billion dollar international project
- potential to discover:
  - 10,000 to 20,000 new pulsars
  - more than 1,000 millisecond pulsars
  - at least 100 compact relativistic binaries!
- probing the equation of state at extreme limits!
- cosmic gravitational wave detector by using pulsars as clocks!

movie
• hyperons have a substantial impact on neutron star properties!

- sizable decrease in the maximum mass of neutron stars due to hyperons!
- hyperons appear at $n = 2n_0$ in neutron star matter
- hyperons are likely to be upsent for a repulsive potential first order phase transition with hyperons possible generates a new, stable solution for compact stars! (besides white dwarfs and neutron stars)
- small and really dense stars presence of hyperons can cool rapidly via hyperon direct URCA process
- hyperon cooling can be suppressed by hyperon pairing, depends on hyperon composition!

future and present facilities: in the sky Chandra, XMM-Newton, INTEGRAL, XEUS, JWST, SKA, and on earth JLab, Daphne, J-PARC, FAIR at GSI !!!
Summary

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- presence of hyperons can cool rapidly via hyperon direct URCA process
- hyperon cooling can be suppressed by hyperon pairing, depends on $\Sigma$ hyperon composition!