Hyperons in neutron stars

Lecture 1

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Density of neutron stars - 1

$G = 6.6732 \times 10^{-8}\ \mathrm{cm}^3\ \mathrm{g}^{-1}\ \mathrm{s}^{-1}$ $\qquad M_\odot = 1.989 \times\ 10^{33}\ \mathrm{g}$

typical NS sizes - 2-3 times Schwarzschild radius r_g

$$\boxed{r_\mathrm{g} = 2GM/c^2 = 2.96 \times (M/M_\odot)\ \mathrm{km}}$$

measured masses and radii vskip 3mm $R \sim 10 - 20\ \mathrm{km}\ ,\ \ M \sim 1 - 2\ M_\odot$

$\overline{\rho} = M/(\frac{4}{3}\pi R^3)$

$$\boxed{\overline{\rho} \sim (10^{14} - 10^{15})\ \mathrm{g\ cm}^{-3}}$$

Central density can be significantly higher

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$$m\Omega^2 R < GMm/R^2 \implies M/R^3 > \Omega^2/G$$

measured pulsar frequency

January 2006: $f = 1/\mathrm{period} = 716 \ \ \mathrm{Hz}$ $\qquad \Omega = 2\pi f = 4499 \ \mathrm{s}^{-1}$

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Neutron stars are the densest stars in the Universe

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Physical conditions in neutron star core - 1

Matter constituents: baryons ($B = N, H$) and leptons ($\ell = e, \mu$) - **Fermions**

Number density of species j

$$n_j = N_j/V$$

Fermi momentum of species j

$$n_j = \frac{p_{\mathrm{F}j}^3}{3\pi^2\hbar^3} \Longrightarrow p_{\mathrm{F}j} = \hbar\left(3\pi^2 n_j\right)^{1/3}$$

BARYONS: non-relativistic, **strongly interacting** Fermi liquid

"Fermi kinetic energy" $\varepsilon_{\mathrm{F}B}^{\mathrm{kin}} = p_{\mathrm{F}B}^2/2m_B^*$

LEPTONS: Quasi-ideal Fermi gases

electrons - ultrarelativistic, muons - mildly relativistic

$$\varepsilon_{\mathrm{F}\ell} = \varepsilon_{\mathrm{F}\ell}^{\mathrm{kin}} = \sqrt{m_\ell^2 c^4 + p_{\mathrm{F}\ell}^2 c^2} - m_\ell c^2$$

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Fermi temperature

$$T_{\mathrm{F}j} = \varepsilon_{\mathrm{F}j}^{\mathrm{kin}}/k_{\mathrm{B}} = 1.16 \times 10^{11} \cdot \frac{\varepsilon_{\mathrm{F}j}^{\mathrm{kin}}}{10 \ \mathrm{MeV}} \ \mathrm{K}$$

After a few months $T < 10^9$ K , and matter constituents are **strongly degenerate** $T/T_{\mathrm{F}j} < 10^{-2}$

For $T < 10^9$ K NS is transparent to neutrinos

Neutrinos are decoupled from the matter, and leave NS in $R/c \sim 10^{-4}$ s

Neutrinos do not affect the matter thermodynamics. Matter is **neutrino-free**

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Baryon sector - notations

B - baryon index, $\quad B = n, p, \Lambda^0, \Sigma^-, \Xi^-, \ldots.$

b - label of baryonic quantity.

$$\sum_B n_B = n_\mathrm{b} \ .$$

The electric charge density and the strangeness per baryon are given by

$$q_\mathrm{b} = \sum_B n_B Q_B \ , \qquad s_\mathrm{b} = \sum_B n_B S_B / n_\mathrm{b} \ .$$

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Energy density of baryon-lepton plasma

$\mathcal{E} = E_{\rm tot}/V$ includes rest energy of particles

uniform plasma at rest $\Longrightarrow$ $\mathcal{E}$ is function of n_j .

Electromagnetic contribution to $\mathcal{E}$ can be neglected compared to kinetic energy and strong interaction energy.

$$\boxed{\mathcal{E}(\{n_j\}) = \mathcal{E}_{\rm B}(\{n_B\}) + \mathcal{E}(n_e) + \mathcal{E}(n_\mu)}$$

Challenge - calculation of $\mathcal{E}_{\rm B}(\{n_B\})$

Important quantity for multicomponent plasma: chemical potential of species j

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electrons - ultra-relativistic

$$\mu_e = \hbar c p_{\mathrm{F}e} \approx 122.1\,(n_e/0.05 n_0)^{1/3}\ \mathrm{MeV}\ ,$$

muons mildly relativistic

$$\mu_\mu = m_\mu c^2 \sqrt{1 + (\hbar p_{\mathrm{F}\mu}/m_\mu c)^2}\ .$$

Muons present only if $\mu_e > m_\mu c^2 = 105.65$ MeV. Otherwise $\mu^- \longrightarrow e^- + \nu_\mu + \overline{\nu}_e$

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Chemical potentials of leptons

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electrically neutral matter at a given baryon number density $n_{\rm b}$

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$$\boxed{q=0} \quad \sum_B n_B Q_B - \sum_{\ell=e,\mu} n_\ell = 0 ,$$

Q_B - electric charge of a baryon B in units of e

Equilibrium state: by minimizing $\mathcal{E} = \mathcal{E}(\{n_B\}, n_e, n_\mu)$ under the constraints $\boxed{n_{\rm b}}$ $\boxed{q=0}$

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NHeμ matter in equilibrium - 1

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NHeμ matter in equilibrium - 2

Auxiliary "energy density" $\widetilde{\mathcal{E}}$

$$\widetilde{\mathcal{E}} = \mathcal{E} + \lambda_{\rm b} \left(\sum_B n_B - n_{\rm b} \right) + \lambda_{\rm q} \left(\sum_B Q_B n_B - \sum_{\ell=e,\mu} n_\ell \right) .$$

$\lambda_{\rm b}$ and $\lambda_{\rm q}$ - Lagrange multipliers

$N_{\rm B}$ - number of the baryon species

Minimizing $\widetilde{\mathcal{E}} \Longrightarrow N_{\rm B} + 2$ equations

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NHeμ matter in equilibrium - 3

Eliminate Lagrange multipliers: $\lambda_{\rm q} = \mu_\ell\ ,\quad \lambda_{\rm b} = -\mu_\ell Q_B - \mu_B$

Therefore $\mu_e = \mu_\mu$ and $-\mu_e Q_B - \mu_B = -\mu_e Q_{B'} - \mu_{B'}$

$N_{\rm B}$ relations for $N_{\rm B} + 2$ chemical potentials

additional relations $\boxed{n_{\rm b}}$ and $\boxed{q = 0}$

Total number of equations $N_{\rm B} + 2$

Equation depends on Q_B

lightest baryons - octet n, p, Λ, Σ, Ξ $Q_B = -1, 0, 1$:

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Q_B = -1 &: \quad \mu_{B^-} = \mu_n + \mu_e\ , \\
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NHeμ matter in equilibrium - 3

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Baryon octet

Table: Masses, electric charges, strangeness, and e-folding (mean) lifetimes of the baryon octet, measured in laboratory. The baryon number, spin, and parity of all these baryons are 1, $1/2$, and $+1$, respectively.

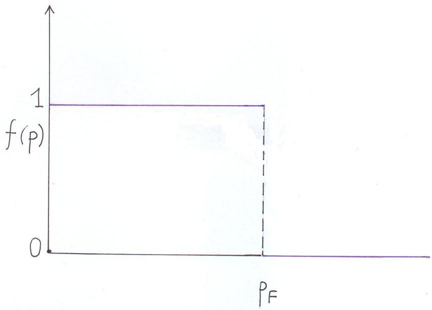
baryon name	mc^2 (MeV)	Q (e)	S	τ (s)
p	938.27	1	0	$> 10^{32}$
n	939.56	0	0	886
Λ^0	1115.7	0	-1	2.6×10^{-10}
Σ^+	1189.4	1	-1	0.80×10^{-10}
Σ^0	1192.6	0	-1	7.4×10^{-20}
Σ^-	1197.4	-1	-1	1.5×10^{-10}
Ξ^0	1314.8	0	-2	2.9×10^{-10}
Ξ^-	1321.3	-1	-2	1.6×10^{-10}

Free Fermi gas, $n = \frac{{p_{\mathrm{F}}}^3}{3\pi^2\hbar^3}$

$n = 2\int \frac{\mathrm{d}^3 p}{(2\pi\hbar)^3} f(p)$

Strongly interacting Fermi liquid - jump in $f(p)$ at p_{F}, same relation between p_{F} and n

Effect of interactions: depleted states $p < p_{\mathrm{F}}$, populated states $p > p_{\mathrm{F}}$



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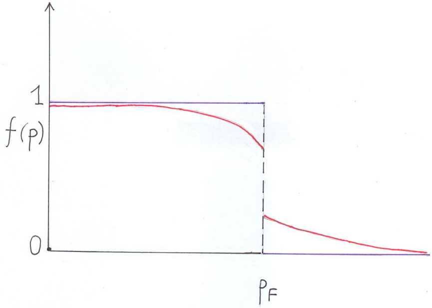

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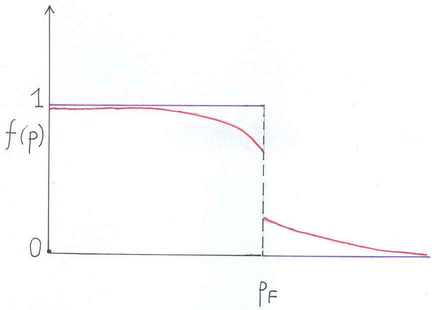
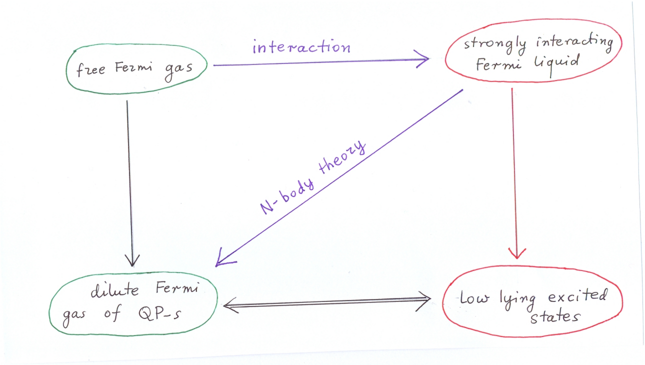


Particles vs. quasiparticles



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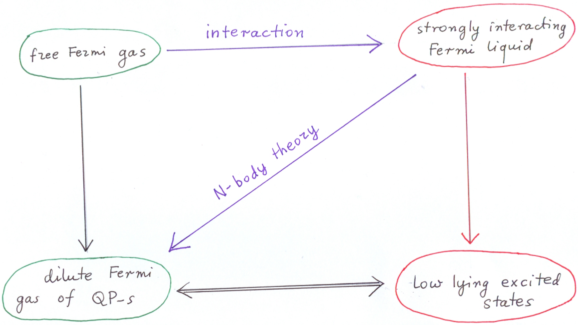

Threshold densities for hyperons. $Q = 0$

$npe\mu$ matter in equilibrium

$V = const, N_{\rm b} = const, T = 0$

$$\boxed{\delta E = -P\delta V + \sum_j \mu_j \delta N_j}$$

$npe\mu$-matter becomes unstable: $\delta N_n = -1$ $\delta N_\Lambda = +1 \Longrightarrow \delta E < 0$

Chemical potential of one Λ in $npe\mu$ matter calculated as a limit:

$$\lim_{n_\Lambda \longrightarrow 0} \left(\partial \mathcal{E}/\partial n_\Lambda\right)_{\rm eq} \equiv \mu_\Lambda^0 \ .$$

$n_{\rm t}^\Lambda$ at which $\mu_\Lambda^0 - \mu_n$ vanishes $\Longrightarrow$ Λ present for $n_{\rm b} > n_{\rm t}^\Lambda$

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ENERGY ARGUMENT

Λ are stable because $\mu_\Lambda^0 - \mu_n < 0$ and therefore
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"Conversion" $n \longrightarrow \Lambda$ will proceed till $\mu_\Lambda = \mu_n$, i.e. till equilibrium between Λ and $npe\mu$ is reached

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QUASIPARTICLE ARGUMENT

Normal Fermi liquids: one-to-one correspondence between

$$\boxed{Strongly\ interacting\ degenerate\ Fermi\ system}$$

and

$$\boxed{Fermi\ gas\ of\ weakly\ interacting\ quasiparticles}$$

Restriction to low-lying excited states: only states close to the ground state are involved: (quasi)particles close to the Fermi surface

$\Lambda \longrightarrow n$ prohibited by **energy conservation** due to the **Pauli principle for quasiparticles**

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Chemical potential of one Σ^- in $npe\mu$ matter is calculated as a limit:

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Find $n_{\rm t}^{\Sigma^-}$ at which $\mu^0_{\Sigma^-} - \mu_n - \mu_e$ vanishes $\Longrightarrow \Sigma^-$ present for $n_{\rm b} > n_{\rm t}^{\Sigma^-}$

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Energy

Σ^- are stable as long as $\mu_{\Sigma^-} - \mu_n - \mu^e < 0$ and therefore $\delta N_n = +1, \delta N_\Lambda = -1 \Longrightarrow \delta E > 0$

Conversion $n, e \longrightarrow \Sigma^-$ will proceed till $\mu_{\Sigma^-} = \mu_n + \mu_e$, i.e. till equilibrium between Σ^- and $npe\mu$ is reached

Argument based on "quasiparticles"

$\Sigma^- \longrightarrow n + e$ is prohibited by the energy conservation due to Pauli principle for quasiparticles

Analogous procedure for Ξ^-

Stability of hyperons in dense matter $Q = -1$

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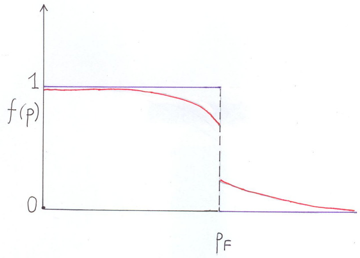
- Strong NN interactions make available energy and momenta significantly larger then the Fermi ones
- Strong process involving high-energy n in initial state, and producing very short-lived final state $\boxed{n + n \longrightarrow n + \Lambda + K^0}$
- Kaon is unstable (no kaon-condensation!) and decays by weak interaction $\boxed{K^0 \longrightarrow 2\gamma}$, and heat is radiated by neutrinos
- Λ downscatters, becomes a quasi-particle dressed by strong interaction and stays in the matter because decays $\Lambda \longrightarrow n + \pi^0$ and $\Lambda \longrightarrow p + e^- + \overline{\nu}_e$ are blocked by the energy & momentum conservation



particle states: very short lived
quasi-particle states - long lived

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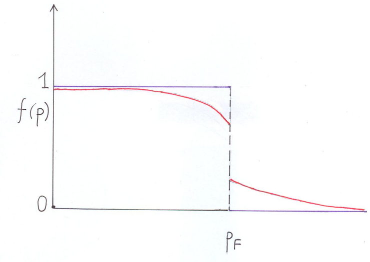

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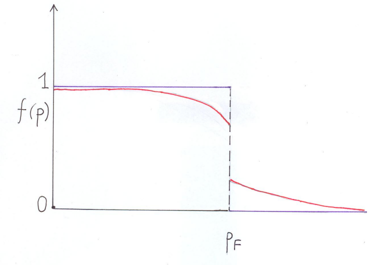

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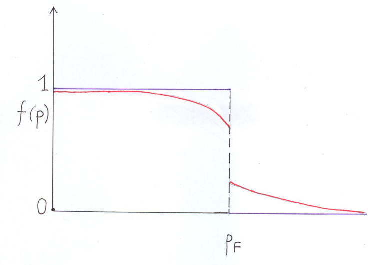

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