Strange Exotic States and Compact Stars

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Outline

- Multi-quark states and neutron stars
  - Light pentaquarks with strangeness
  - Heavy pentaquarks and multi-quark states with charm
  - Pentaquarks in the medium and in neutron stars
  - Constraints for pentaquarks from pulsar mass measurements
- Signals for strange quark matter in compact stars
  - pulsar kicks
  - gamma-ray bursts
  - gravitational waves
- Summary
Multi–Quark States and Neutron Stars
Multi-Quark States: Some History (incomplete)

- multi-quark states already mentioned by Gell-Mann in 1964
- strange four-quark states (qsq̄s): Jaffe 1977
- heavy tetraquarks (QQq̄q): Ader, Richard, Taxil 1982
- pentaquarks with charm (qqqs̄c): Lipkin 1987 and Gignoux, Silvestre-Brac, Richard 1987

... 

- light pentaquark (qqqq̄s) in chiral soliton model: Diakonov, Petrov, Polyakov 1997
- light pentaquark in diquark model: Jaffe and Wilczek 2003
Pentaquark/Multiquark candidates

- detection of pentaquark $\Theta^+$ first reported in 2003
- mass 1.54 GeV, small width (<1 MeV)
- experimental situation for $\Theta^+$ today: conflicting! (PDG status 2005 down to **)
buts not hopeless $\rightarrow$ talk by Nakano!

- $\Theta^{++}$ seen by STAR in dAu data? (not in pp, AuAu)
- $H$ dibaryon signal seen by STAR? (PhD thesis of Renaud Vernet)!
- NA49 reports on $\Xi(1860)$ pentaquark (ssdd$\bar{u}$)
- charmed pentaquark $\theta_c(3100)$ (uudd$\bar{c}$) reported by H1 collaboration
Multi-quark states with charm: charmlets

(JSB and A. Vischer, PRD 57 (1998) 4142)

- unified bag model for light (color-magnetic potential) and heavy quarks (color-electric potential)
- shell-model calculation: hexaquark candidates
  \( \{\text{cssuud}\}^+, \{\text{cssudd}\}^0, \{\text{ccsuud}\}^{++}, \{\text{ccsuud}\}^+, \{\text{ccssud}\}^+ \)
- production rates at RHIC: \(10^{-3}\) to \(10^{-2}\) per event
- direct charm measurements with future micro-vertex detectors!

J. Schaffner-Bielich, Goethe University, Frankfurt – p.6/27
Pentaquarks in the medium: $\Theta^+$ hyponuclei?

- **Quark Model:** stable $\Theta^+$ in nuclei!
  - critical potential: $U(\Theta^+) < -105$ MeV (Miller 2004)
- **RMF model:** $U(\Theta^+) = -50$ to $-90$ MeV
  (Zhong, Tan, Peng, Li, Ning 2005)
- **QCD sum rules:** $U(\Theta^+) = -40$ to $-90$ MeV
  (Navarra, Nielsen, Tsushima 2005)
- **Hadronic SU(3) approach:** $U(\Theta^+) = -60$ to $-120$ MeV
  (Cabrera, Li, Magas, Oset, Vicente Vacas 2005)
- **Quark mean-field model:** $U(\Theta^+) \approx -50$ MeV
  (Shen and Toki 2005)

Note: $\Theta^+$ can explain long-standing puzzle (missing reactivity) in $K^+$-nucleus reactions! (Gal and Friedmann 2005, Tolos, Cabrera, Ramos, Polls 2006)
Pentaquarks in dense matter: neutron stars

maximum mass of neutron stars: > $2M_\odot$ for nucleons plus leptons only

- reduced by hyperons to $M < 2M_\odot$

- even further reduced by pentaquarks!

- maximum mass sensitive to $\Theta^+$ potential!

(see poster by Mirjam Wietoska)
Composition of neutron stars with pentaquarks

(M. Wietoska, JSB, 2006)

- Hyperons appear around $2n_0$
- $\Theta^+$ appear around $4n_0$ (for $U(\Theta^+) = -100$ MeV at $n_0$)
- For the maximum mass star: about 5% $\Theta^+$ in the core
Maximum mass for $\Theta^+$ neutron stars

$\Theta^+$ can appear even for $U(\Theta^+) = +50$ MeV!

for $M > 1.6M_\odot$, the potential depth $U(\Theta^+) > -190$ MeV

$\Rightarrow$ weak constraint on $\Theta^+$ potential

pulsar mass measurements $\Rightarrow$ talk by Ingrid Stairs!

(M. Wietoska, JSB, 2006)
Pulsar Mass Constraints for $\Theta^-$ in matter

\begin{itemize}
\item for $M > 1.44 M_\odot$: potential depth $U(\Theta^-) > -55 \ldots -125$ MeV
\item for $M > 1.60 M_\odot$: potential depth $U(\Theta^-) > 0 \ldots -85$ MeV
\item $\Rightarrow$ strong constraint on $\Theta^-$ potential
\end{itemize}

(M. Wietoska, JSB, 2006)
Signals for Strange Quark Matter in Compact Stars
Hunting down strange quark matter in the heavens

Coming of age! Some recently suggested signals:

- ’exotic’ mass-radius relation of compact stars
- enhanced cooling of neutron stars
- gamma-ray bursts by transition to strange quark matter
- gravitational wave signals of collisions of compact stars with quark matter (3D in General Relativity)
- pulsar kicks by asymmetric emission of neutrinos from quarks:
  - check for the energetics (enough kick?)
  - check for the anisotropy (enough polarization?)
  - check for the neutrino rocket (do they come out?)
  - see poster by Irina Sagert
Pulsar kicks: speeding neutron stars!

- pulsars moving out of the center of the supernova remnant
- high space velocities observed: up to 1600 km/s ! (Hobbs 2005)
- highest directly measured kick velocity: $1080 \pm 100$ km/s (Chatterjee et al. 2005)
- kick axis closely aligned with rotational axis (Crab, Vela, B0656+14)
energy stored in neutrinos: 99% of total supernova energy!

kinetic energy of pulsar kick: 1% of energy stored in neutrinos

asymmetry of 1% for neutrino emission sufficient for kick!
Pulsar kicks by asymmetric neutrino emission

\( R \text{ [km]} \)

\( T \text{ [10^{10} K]} \)

\( \alpha_s = 0.5, \mu_q = 400 \text{ MeV}, M_{\text{ns}} = 1.4 M_{\odot}, \chi = 1 \)

(Sagert, JSB, 2006)

- electron capture on quarks: parity-violating
- \( \rightarrow \) anisotropic production of neutrinos for degenerate matter!
- \( \rightarrow \) need just about \( T = 5 \text{ MeV} \) for sufficient pulsar kick

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Polarization by ultrastrong magnetic fields

- surface magnetic fields of pulsars: typically $B \approx 10^{12}$ Gauss
- magnetars: up to $10^{15}$ Gauss!
- magnetic field in (quark) core: up to $10^{18}$ Gauss possible
- electrons in strong magnetic fields: moving in Landau levels
- lowest Landau level: fully polarized!

(Sagert, JSB, 2006)
Mean-free paths of neutrinos in dense and hot matter

(Reddy, Sadzikowski, Tachibana 2003)

<table>
<thead>
<tr>
<th>phase</th>
<th>process</th>
<th>$\lambda$ (T=5 MeV)</th>
<th>$\lambda$ (T=30 MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Matter</td>
<td>$\nu n \rightarrow \nu n$</td>
<td>200 m</td>
<td>1 cm</td>
</tr>
<tr>
<td></td>
<td>$\nu e n \rightarrow e^- p$</td>
<td>2 m</td>
<td>4 cm</td>
</tr>
<tr>
<td>Unpaired Quarks</td>
<td>$\nu q \rightarrow \nu q$</td>
<td>350 m</td>
<td>1.6 m</td>
</tr>
<tr>
<td></td>
<td>$\nu d \rightarrow e^- u$</td>
<td>120 m</td>
<td>4 m</td>
</tr>
<tr>
<td>CFL</td>
<td>$\nu \rightarrow H\nu$</td>
<td>100 m</td>
<td>70 cm</td>
</tr>
<tr>
<td></td>
<td>$\nu \phi \rightarrow \nu \phi$</td>
<td>$&gt;10$ km</td>
<td>4 m</td>
</tr>
</tbody>
</table>

- small mean-free path in nuclear matter
- larger mean-free path in quark matter
- color-flavor locked phase: in principle huge mean-free path
- massless excitation (H): mean-free path similar to normal quark matter!
- size of coupling strength of H well determined! (thanks Sanjay!)
Mean-free path of neutrinos and kick velocity

- Problem: Neutrinos have to get out without rescattering to preserve anisotropy.
- Mean-free path too short at $T = 5$ MeV!

(Sagert, JSB, 2006)
Pulsar kicks for color superconducting quark matter

- increase mean-free path exponentially with gap: $\sim \exp(-\Delta/T)$
- but thermal energy (specific heat) decreases exponentially, too!
- both curves (kick velocity and mean-free path) are shifted up
- $\implies$ need some mechanism to increase specific heat of color superconducting quark matter (Goldstone modes?)

(Sagert, JSB, 2006)

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Gamma-ray bursters

- highly energetic events in the sky
- energy release similar to supernova energies!
- about one gamma-ray burst per day!
- sources: colliding neutron stars, stars collapsing to black holes or collapsing compact stars!
subsample with long quiescent periods (>40 s) extracted (BATSE catalog)

similar characteristics of the bursts before and after quiescence

points to a dormant inner engine (not related to pulsar wind)!

hints at a collapse of a neutron star with two phase transitions: first to quark matter then to color–superconducting matter!?!
Summary

- charming multiquark states: do not miss to look for it!
- light pentaquark states can be present in neutron star cores
- light pentaquark in-medium properties can be constrained by pulsar mass measurements
- strange quark matter can signal itself in astrophysical observables
- high-velocity pulsars observed (pulsar kicks): relation to formation of strange quark matter in core?
- gamma-ray bursts with long quiescence times: phase transitions to normal then to color-superconducting quark matter?
- much more astro data on the horizon, a lot of opportunities → cross-talk with observers needed!!!
Composition of neutron stars with $\Theta^-$

(hypothetical) negatively charged $\Theta^-$ appears at $2n_0$

$\Theta^-$ present as first exotic/strange component!

maximum density only $3.3n_0$

(M. Wietoska, JSB, 2006)
Pulsar Mass Constraints for $\Xi^{--}$ in matter

$\Xi^{--}$ with 1.60 $M_{\text{sun}}$

Potential depth [MeV]

Mass of $\Xi^{--}$ [MeV]

(M. Wietoska, JSB, 2006)

Pentaquark $\Xi^{--}$: only small masses and strongly attractive potentials are incompatible with pulsar mass measurements
Pulsar kick explanations

- deformed neutrino-sphere in magnetic fields, emission of sterile neutrinos (Kusenko, Segre, 1997)
  needs exotic particles (sterile neutrinos)!

- parity-violating neutrino emission in strong magnetic fields in nuclear matter (Li, Horowitz 1998)
  only surface emission, needs large magnetic fields at surface!

- spin–1 color superconductivity (Schmitt, Shovkovy, Wang, 2005)
  too low kick velocities!

- electromagnetic vortices in color–superconducting (CSC) quark matter (Berdermann, Blaschke, Grigorian, Voskresensky, 2005)
  no electromagnetic vortices in standard CSC quark matter!

- anisotropy in neutrino-driven supernova explosion (Scheck, Kifonidis, Janka, Müller, 2006)
  needs artificially increased $\nu$–interaction for successful explosion!
Gravitational wave signal from strange quark matter?

- **binary neutron star mergers with a quark core:** signal clearly seen in different Fourier spectrum!  
  (Oechslin, Uryū, Pogosyan, Thielemann 2004)

- **binary strange quark star collision:** higher frequencies possible before ‘touch-down’ compared to normal neutron stars  
  (Limousin, Gondek-Rosinska, Gourgoulhon 2005)

- **collapse of neutron star to quark matter:** sensitive to EoS  
  (Lin, Cheng, Chu, Suen 2006)