1. Introduction

In the spirit of this session on exotic quark states, strange quark matter and astrophysics, we are going to discuss the interrelation of these seemingly different topics. First, we give a brief discussion on multiquark states, in detail we address the properties of multiquark states with strangeness and charm. We consider light pentaquarks with strangeness then heavy pentaquarks and multi-quark state with charm. We summarise the current understanding of the in-medium properties of pentaquarks in cold dense matter and extrapolate it to the case of neutron star matter in beta-equilibrium. The possible appearance of various pentaquark states and its implications for the global properties of neutron stars is analysed and confronted with recent pulsar mass measurements.

In the second part of this talk, we present newly suggested signals for the possible presence of strange quark matter in the core of compact stars. In particular, we focus on the phenomenon of pulsar kicks, which has received considerable attention recently. The recent detailed measurements of velocities of nearby pulsars in our galaxy clearly shows, that speeds in excess of 1000 km/s are involved, much higher than the typical velocity of ordinary nearby stars. So far a generally accepted explanation for this effect is not at hand. In addition, we briefly comment on recent developments on the relation of gamma-ray bursts with strange quark matter and the recent gravitational wave signals derived for the presence of strange quark matter in compact stars.

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2. Multiquark States and Neutron Stars

2.1. Multi-Quark States: Some History (incomplete)

The possible existence of multi-quark states, i.e. hadronic states with more than three quarks, has been a topic of investigations for decades since it was mentioned as a possibility within the quark model by Gell-Mann in 1964 \[1\]. The first detailed predictions of a bound multi-quark state was put forward by Jaffe in 1977: four-quark states with strangeness (qs\bar{s}) \[2\], and the famous H-dibaryon, a six-quark state with equal numbers of up-, down-, and strange quarks (uuddss) \[3\]. Shortly afterwards, the possibility of having bound multi-quark systems with heavy quarks (QQ\bar{q}\bar{q}) were considered, too, in particular for the heavy tetraquark systems, which consist of two light antiquarks and two heavy quarks (or vice versa) \[4\]. It was shown that heavy tetraquarks must be bound in the limit of infinite heavy quarks. Interestingly, pentaquark states were first proposed with a charm anti-quark (qqqs\bar{c}) in 1987 \[5, 6\]. Lipkin considered symmetry arguments for the four light quarks within SU(6) to show that the pentaquark can be a bound state, i.e. the decay to a baryon and a meson is energetically forbidden. These arguments cannot be applied to a pentaquark state with an antistrange quark and four light quarks consisting of up- and down-quarks only (qqqq\bar{s}). Exactly such a pentaquark state was proposed as a sharp resonant state by Diakonov, Petrov, Polyakov in 1997 \[7\] on the basis of the chiral soliton model. Key entry for its stability is the hypercharge, not the spin-colour structure of the interaction. The light pentaquarks are grouped within an antidodecuplet, the lightest candidate, the Θ\[^+\] being on the top of the triangle. The light pentaquarks can be also described by the diquark model of Jaffe and Wilczek \[8\], which takes into account the recent developments of colour superconductivity and strong diquark pairing in QCD.

As is well known in this community, the light pentaquark Θ\[^+\] has received enormous interest as several experimental groups reported a signal for observing a pentaquark state starting in 2003. The mass is 1.54 GeV and it has a small width of less than 1 MeV. The experimental situation is conflicting today, the experimental status of confidence as given by the particle data group went down to only two stars in 2005. But the experimental situation is not hopeless and we refer to the corresponding overview talk given by Nakano at this meeting for more details. We note that the antiparticle partner, the Θ\[^-\] has been observed by the ZEUS collaboration \[9\].

In addition, other multiquark states have been reported recently also for heavy-ion collisions. A possible signal for the Θ\[^++\] and its antiparticle Θ\[^--\] has been seen by the STAR collaboration in d-Au collisions (but not in p-p or Au-Au collisions) \[10, 11\] and for the H-dibaryon \[12\]. NA49 reports on detecting a signal for the doubly strange Ξ(1860) pentaquark (ssdd\bar{u}), which is a member of the light pentaquark antidodecuplet \[13\]. Finally, a charmed pentaquark Θc(3100) (uudd\bar{c}) state was detected by the H1 collaboration \[14\].
2.2. Multi-quark states with charm: charmlets

Charm quarks have a stabilising effect for multiply charmed quark states. First, due to its heavy mass a shallower potential is needed to bind the system. Second, the colour-electric interaction between heavy quarks is highly attractive. Third, the light quarks can combine to a favourable antisymmetric flavour state for non-colour singlet states. The latter fact is for example the reason why the charmed pentaquark gets some additional binding energy compared to its possible decay products [5], while the first two apply for e.g. the heavy tetra-quark states [4].

Bulk charmed strange quark matter turns out to be deeply bound within the MIT bag model when including effects from single-gluon exchange [15] even for large values of the MIT bag constant. Therefore, charmed strange quark matter can form bound objects even for the case when ordinary strange quark matter (without charm quarks) is unbound. For the description of multiply charmed quark states, as e.g. for the charmonium states, it is essential to include explicitly the colour-electric interaction terms. This modified bag model can describe reasonably well both, light nonstrange and strange hadrons as well as charmed hadrons with a slightly larger bag constant [15] compared to the standard MIT bag model [16]. A shell-model calculation of multiply charmed and strange quark states, however, does not give bound candidates. The primary reason for this result originates from the effectively added Casimir energy which favours ordinary hadronic states over many-quark states. Possible candidates close to being bound are the hexaquark states \{\text{cssuud}\}^+, \{\text{cssudd}\}^0, \{\text{ccsuud}\}^{++}, \{\text{ccsuud}\}^+, and \{\text{ccssud}\}^+. Those exotic objects can be produced in collisions of heavy-ions at relativistic bombarding energies. The production rates at RHIC amount to $10^{-3}$ to $10^{-2}$ per event within a simple coalescence model [15]. Direct charm measurements will be possible with the PHENIX and STAR detectors at RHIC with their upgrade in the near future using e.g. micro-vertex detectors! A unique signal would be a double star event on typical timescales of the weak decay of charmed hadrons, i.e. within 100 micron or so. Note, that the same event pattern, a double star, lead to the discovery of hypernuclei in 1953 [17]!

2.3. Pentaquarks in the medium: $\Theta^+$ hyponuclei?

Hypernuclei are bound systems of nucleons with usually one or two hyperons, the more general term strange hadronic matter applies to bound systems of nucleons and multiple hyperons in general (see e.g. [18] and references therein). In particular $\Lambda$ hypernuclei have been studied extensively experimentally and theoretically and attractive optical potentials of $U(\Lambda) \approx 30$ MeV have been extracted from hypernuclear data. It is straightforward to imagine, that the light strange pentaquarks can form similarly bound objects with nuclei. So called hyponuclei (see e.g. the historical note in [19]) have been considered in the literature for $\Theta^+$ pentaquarks. The simple quark model gives a highly attractive potential for the $\Theta^+$, in fact the real part of the optical potential can be below the critical value of $U_c(\Theta^+) = -105$ MeV so that the $\Theta^+$ can not decay to a $\Lambda$ and a
Strange Exotic States and Compact Stars

kaon anymore and is stabilised in nuclei [20]! Within the relativistic mean-field model, potential depths for the $\Theta^+$ of $U(\Theta^+) = -37.5$ to $-90$ MeV at normal nuclear matter density $n_0$ have been considered [21, 22]. QCD sum rule estimates arrive at similar values of $U(\Theta^+) = -40$ to $-90$ MeV [23]. A more general hadronic SU(3) approach allows for $U(\Theta^+) = -60$ to $-120$ MeV if including coupling to two-meson channels [24]. Finally, a quark-mean field model favours $U(\Theta^+) \approx -50$ MeV [25]. Interestingly, the presence of the $\Theta^+$ in reactions of kaons with nuclei can explain the long-standing puzzle of its missing reactivity which was put forward by Gal and Friedman [19] and outlined in detail within a coupled-channel calculation by Tolos, Cabrera, Ramos, and Polls [26].

2.4. Pentaquarks in Neutron Stars

Now it is well known, that exotic and strange particles can be present in high-density matter in the core of neutron stars. Hyperons for example appear around twice normal nuclear matter density (see e.g. the discussion in [27] and references given therein). While the maximum mass of neutron stars is larger than $2M_\odot$ for matter consisting of nucleons and leptons only, it is reduced considerably below that value when the effect of hyperonisation is taken into account [28]. The maximum mass can be further reduced when more exotic species are present at high densities. Every new degree of freedom reduces in principle the pressure for a given energy density for a free Fermi gas. Strong interactions for quarks, however, can invalidate that argument and can lead to compact stars with strange quark matter cores with maximum masses close to $2M_\odot$ [29].

In the following we explore the possibility that pentaquarks can affect the maximum mass of compact stars and derive limits for their maximum attainable attractive potential in dense matter for the case of purely hadronic compact stars (see [30] for details). In fact, we find that the presence of $\Theta^+$ leads to an overall reduction of the maximum mass of compact stars, similar to the case of hyperons, so that such constraints can be derived. We consider the relativistic mean-field model with nucleons, leptons and hyperons, where the interaction is mediated by the exchange of scalar ($\sigma, \sigma^*$) and vector mesons ($\omega, \rho, \phi$) using SU(6) symmetry relations for the coupling constants of the vector mesons and adjusting the potential depth with the scalar coupling constants appropriately [31, 32, 33, 13]. The coupling constants for pentaquarks are chosen similarly. We use the naive quark counting rule for fixing the relative vector coupling strength. The scalar coupling constant is determined by choosing a potential depth of the pentaquark at normal nuclear matter density and varied accordingly. We adopt a negative vector coupling strength as advocated in [23] using QCD sum rules. Note, that in any case the pentaquark, like the other baryons, feels an overall repulsive (vector) potential at high densities, which garantees the stability of matter (otherwise matter will continously increase its density and collapse to a black hole)!

The model under study predicts that hyperons are present in neutron star matter around twice normal nuclear matter density [33]. Assuming a potential depth of the $\Theta^+$ pentaquark at normal nuclear matter density of $U(\Theta^+) = -100$ MeV, it will appear
Strange Exotic States and Compact Stars

around $4n_0$ in beta-equilibrated dense matter. For the maximum mass configuration, the fraction of pentaquarks in the core of the compact star amounts to about five percent.

The $\Theta^+$ can appear even for a repulsive potential of $U(\Theta^+) = +50$ MeV at $n_0$. The reason is that the repulsive potential felt by the pentaquark rises less steeply with density compared to the nucleon one, so that it will become comparably smaller which allows for pentaquarks to emerge in sufficiently high density matter. The presence of pentaquarks reduces the overall pressure, so that the maximum mass decreases. The change is, however, quite small, so that the constraints on the pentaquark in-medium potential are moderate. Recent pulsar mass measurements of pulsar binaries with white dwarfs point towards $M > 1.6 M_\odot$, see the presentation given by Ingrid Stairs at this meeting. For a pulsar mass of $M > 1.6 M_\odot$, the potential depth of the pentaquark must be $U(\Theta^+) > -190$ MeV (for parameter set GM1 of [25]) which is a rather weak constraint.

The same line of reasoning can be adopted for other possible pentaquark states. In particular, we expect that negatively charged states are favoured in compact star matter as charge balance with the positively charged protons can be more easily accomplished. Indeed, pulsar mass constraints for a hypothetical negatively charged pentaquark $\Theta^-$ in matter lead to much stronger limits: $U(\Theta^-) > -55\ldots -125$ MeV for $M > 1.44 M_\odot$ and $U(\Theta^-) > 0\ldots -85$ MeV for $M > 1.6 M_\odot$. The range indicates the values found for various different parameter sets, see [30]. The composition of compact stars with $\Theta^-$ pentaquarks shows even more drastic changes compared to an ordinary neutron star. The negatively charged $\Theta^-$ appears already at $2n_0$ (for $U(\Theta^-) = -100$ MeV and set GM1) being the first exotic and strange component in beta-equilibrated matter! The maximum density attainable for stable compact star configurations is reduced to only $3.3n_0$. The doubly negative charged pentaquark $\Xi^{--}$ is a member of the pentaquark antidecuplet. However, the effect of having twice the negative charge is compensated by the proposed (and measured) much heavier mass of the $\Xi^{--}$ of around 1860 MeV. Constraints on its in-medium potential turn out to be rather weak, only hypothetical small masses and large attractive potentials are incompatible with pulsar mass measurements.

3. Signals for Strange Quark Matter in Compact Stars

Now we turn to the second topic of this presentation, discussing recently suggested signals for the presence of strange quark matter in compact stars. We will be rather brief without any intention to give an overview on this topic (which is impossible for this booming research field) and focus on topics which are heavily biased towards personal work.

In any case, hunting down strange quark matter in the heavens is certainly coming of age! Some recently suggested signals include besides 'exotic' mass-radius relation of compact stars and the enhanced cooling of neutron stars, gamma-ray bursts by the transition to strange quark matter, gravitational wave signals of the collisions of
compact stars with quark matter, and pulsar kicks by asymmetric emission of neutrinos from quarks. We will concentrate on the latter issue in the following with some small remarks on the other two.

3.1. Pulsar kicks and strange quark matter

There are nearly three-hundred measurements of pulsar velocities recently and it has been observed that the pulsars move out of the centre of the supernova remnant with high space velocities of up to 1600 km/s (see [34] and references therein). The highest directly measured kick velocity has been determined to be $1080 \pm 100$ km/s [35]. So pulsars are speeding through our Galaxy!

We note in passing that the distribution of pulsar kick velocities has been found in some earlier work to be bimodal [36] which has been connected to the coexistence of neutron stars and quark stars by Bombaci and Popov [37], where the quark stars experience a second kick due to the phase transition from hadronic to quark matter (see also [38]).

For three pulsars (Crab, Vela and pulsar B0656+14) the observed kick axis is closely aligned with the rotational axis. Several explanations for the puzzling pulsar kick phenomenon have been put forward as (with some comments in brackets):

- the asymmetric emission of sterile neutrinos from a deformed neutrino-sphere due to magnetic fields [39] (this relies on the properties of hypothetical exotic particles)
- parity-violating neutrino emission in strong magnetic fields in nuclear matter [40] (only surface emission is possible, large magnetic fields at the surface are needed)
- spin–1 colour superconductivity produces asymmetric emission of neutrinos [41] (operates only below a temperature of 1 MeV, so that the resulting kick velocities are too small)
- electromagnetic vortices in colour–superconducting quark matter [42] let neutrinos propagates preferable along the magnetic field axis (however, there are no electromagnetic vortices in the standard colour-superconducting phases considered)
- anisotropy of the hydrodynamic shock wave in neutrino-driven supernova explosion [43] (which needs an artificially increased $\nu$–interaction for successful simulation of an explosion)

Pulsars are born in core-collapse supernovae, first as hot proto-neutron stars. The energy stored in neutrinos amounts to 99 percent of the total energy released in a supernova (of type II). The momentum necessary for the observed pulsar kick velocities is about one percent of the one stored in neutrinos, so that an asymmetry of one percent for neutrino emission is sufficient for a successful kick! However, besides the energetics (enough kick?) also the anisotropy (enough polarisation?) and the efficiency of the neutrino rocket (do they come out?) has to be checked carefully. In the following, we address these issues for getting a kick out of strange quark matter by asymmetric neutrino emission in strong magnetic fields (for details see [44]).
Electron capture on quarks is parity-violating, so that in principle anisotropic production of neutrinos for degenerate matter can occur. If all neutrinos released from the proto-neutron star are emitted along one direction, an initial temperature of just about \( T = 5 \) MeV is needed for a sufficient pulsar kick of 1000 km/s which follows from momentum conservation and the total thermal energy available. Hence, the kick originates from the early proto-neutron star evolution, say within the first minute of the supernova event, and not from later stages.

For asymmetric neutrino emission, we consider here the case of polarisation by ultrastrong magnetic fields. The measured surface magnetic fields of pulsars are typically around \( B \simeq 10^{12} \) Gauss. In certain cases, for so called magnetars, surface magnetic fields of up to \( 10^{15} \) Gauss have been inferred. Moreover, the magnetic field in the quark core can be much larger than at the surface so that magnetic fields in quark matter of up to \( 10^{18} \) Gauss are possible. The electrons are moving then in Landau levels, even in degenerate matter. The lowest Landau level is fully polarised, electron capture on these electrons produce neutrinos which are emitted along one specific direction.

The last criterion for a successful neutrino rocket involves the mean-free paths of neutrinos in dense and hot matter (do they come out?). The scattering reaction \( \nu + n \rightarrow \nu + n \) and the capture reaction \( \nu_e + n \rightarrow e^- + p \) occur in neutron matter and lead to mean-free paths of just a few meters for a temperature of \( T = 5 \) MeV \cite{45}. For unpaired quark matter, similar processes give a mean-free path of around 100 meters. Processes with fully paired quarks, as present in the colour-flavour-locked phase (CFL), are exponentially suppressed, so that CFL quark matter should be transparent to neutrinos. However, the CFL phase violates baryon number conservation and breaks a \( U(1) \) symmetry. The corresponding massless excitation, the \( H \), reduces the mean-free path back to the small values for ordinary quark matter, unfortunately \cite{45}!

So now the problem is that neutrinos have to get out without rescattering to preserve the anisotropy, but the mean-free path is too short, shorter than the typical radius of a neutron star of 10 km at a temperature of \( T = 5 \) MeV. When effects from the \( H \) are ignored, the mean-free path increases exponentially with the gap proportional to \( \exp(-\Delta/T) \). But the thermal energy (the specific heat) stored decreases then exponentially, so that not enough momentum is available for a sufficiently high kick velocity! What is needed then is some mechanism to increase the specific heat of colour superconducting quark matter, maybe by including effects from Goldstone modes.

### 3.2. Gamma-ray bursters and strange quark matter

The phenomenon of gamma-ray bursts are one of the most energetic events observed in the sky, the energy released is similar to the ones of supernovae. About one gamma-ray burst is measured per day. The most promising sources considered so far involve colliding neutron stars, stars collapsing to black holes or collapsing compact stars! Recently, a signal from quiescent gamma-ray bursters has been proposed by Pagliara and Drago \cite{46}. They extracted a subsample with long quiescent periods (more than 40 seconds)
Strange Exotic States and Compact Stars

from the BATSE catalog. Interestingly, the bursts before and after quiescence exhibit a similar characteristic which points to a dormant inner engine rather than to physics related to e.g. the pulsar wind. The properties of long quiescent gamma-ray burster hint then at a collapse of a neutron star with two phase transitions: the first transition proceeds from nuclear matter to quark matter, the second one to colour–superconducting matter releasing the gap energy of gapped strange quark matter!

3.3. Gravitational wave signal from strange quark matter?

There has been a dramatic advancement in recent years in the field of simulating and modelling the gravitational wave signal from compact stars which takes into account effects from the presence of quark matter. Binary neutron star mergers have been simulated including a quark matter equation of state at high densities [17]. The different equations of state affect clearly the Fourier spectrum of the gravitational wave emitted. Binary strange star collisions have been studied in [18]. Compared to ordinary neutron stars, strange stars cause higher frequencies in the gravitational wave signal before ‘touch-down’ due to being more compact in the cases studied by the authors. A collapse of a normal neutron star to a compact star with a quark matter core has been modelled in [19]. Again, the gravitational wave pattern exhibits sensitivities to the underlying equation of state!

4. Summary

We have discussed multiquark states, with strangeness and with charm, and used pulsar mass measurements to derive constraints on the in-medium properties of light pentaquark states. Multiply charmed multiquark states have unusual properties and can be bound by strong colour-electric forces. Double prong decay patterns can signal their existence, if bound, and can be measured with the future tracking devices for charmed particles of the PHENIX and STAR detectors at RHIC. One should not miss this opportunity and look for it! Light pentaquarks, i.e. five-quark states with strangeness, can be present in the core of neutron stars and reduce the maximum mass. Hence, their in-medium properties can be constrained by pulsar mass measurements. Present limits give only loose bounds, which become much tighter with only a slightly increased pulsar mass limit. We are looking forward to ongoing and future pulsar scans and continued observations of binary pulsars which will reduce the uncertainty considerably in the near future!

The presence of strange quark matter in compact stars can signal itself in various astrophysical observables. The puzzling observation of high velocity pulsars might be related to the presence of strange quark matter in pulsars. The conditions for a successful neutrino rocket, the asymmetric emission of neutrinos due to polarised electrons in magnetic fields, have been examined in detail. Large magnetic fields are needed, which might be present in the quark core of compact stars. Enough kick is reached if the
asymmetric emission of neutrinos starts at high enough temperature which is only reached in the early evolution of the proto-neutron star stage, i.e. within a minute after the supernova collapse. At these temperatures, however, the neutrino mean-free path is shorter than the radius of the compact star, in particular in neutron matter. Sufficiently large values are reached for colour-superconducting quark matter in the CFL phase only, if effects from a massless excitation, the so called H, are ignored. However, then the specific heat and the available thermal energy is reduced exponentially so that not enough kick can be produced. Hence, our present understanding of high-density QCD and colour-superconductivity does not give large enough mean-free paths or sufficiently large heat capacities to allow for a successful neutrino rocket. More detailed investigations are needed to pursue this issue in more detail.

The burst pattern of gamma-ray bursters with long quiescence times might indicate the presence of two separate phase transitions in compact stars: one from nuclear matter to normal quark matter then the second one to colour-superconducting quark matter. Also gravitational wave patterns can exhibit the presence of strange quark matter in compact stars either from compact star mergers or from collapsing neutron stars.

Last but not least much more astrophysical data is on the horizon poised for discovery. There are lots of opportunities for strange quark matter physics. Certainly, the cross-talk with observers will be crucial and vital for a successful advancement of strange astrophysics!

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Strange Exotic States and Compact Stars

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