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Physics and Neutron Star Interiors

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Physics and neutron star interiors

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Conditions in neutron stars are more extreme than almost any encountered on Earth: densities exceed those of atomic nuclei, and matter has a large neutron excess. During the past quarter of a century, the challenge of understanding neutron stars has stimulated physicists to confront conditions far different from those normally encountered terrestrially. Laboratory studies have in turn yielded important input for the studies of neutron stars. We discuss a number of examples of this continuing interplay between physics and astrophysics. The first is the equation of state of dense matter, which is the basis for all theoretical models of neutron stars. The second is the composition of dense matter. This has profound influence on neutrino generating processes in neutron stars, and hence on their cooling. A third example is nuclei with a large neutron excess, such as are expected to be present in the crusts of neutron stars. Properties of similar nuclei play an important role in theories of element production.

1. Historical background

Before their observational discovery, neutron stars could be regarded as purely hypothetical objects, suitable for study only by professional astrophysicists. However, once pulsars had been identified as neutron stars, they became a legitimate object of interest for physicists from a wide range of backgrounds, and they began to exert a strong influence on studies of the physics of dense systems, nuclear physics, and other branches of physics. We shall use the 25th anniversary of the discovery of pulsars as an occasion to look back and survey the impact of their discovery on our understanding of the physics of dense matter, and to explore some contemporary themes.

The first subject we discuss is microscopic theories of the properties of dense matter. In the late 1960s workers on dense quantum-mechanical systems could be divided, broadly speaking, into two groups that tended to study different applications, and used different methods. In the problems of interest to nuclear physicists, interactions between nucleons have repulsive cores which are much softer than typical potentials between atoms, which are the interactions encountered by condensed-matter physicists. Internucleon potentials are usually of a Yukawa type, and behave as some low inverse power of the separation r for small separations. Calculations of nuclear properties were based on the idea that at nuclear density, nuclear matter is a relatively dilute system. The key idea of the theory was that the most important configurations of particles were those in which two interact

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simultaneously, and that configurations with more particles interacting were less important. The dimensionless parameter in the theory, $\kappa \sim \rho a^3$, sometimes referred to as the 'wound' in the wave function, measures the fraction of space in which particle interactions play an important role. Here ρ is the density of particles, and a is a characteristic length scale of correlations between particles. For nuclear matter κ was estimated to be about 0.15 (Bethe 1971). The theoretical tool used to implement the programme was quantum-mechanical perturbation theory, and the theory is usually referred to as Brueckner–Bethe–Goldstone theory. Bethe (1971) gave a comprehensive review of the theory which reflects its development shortly after pulsars were discovered. At the time, it was generally believed that the theory should give reliable results up to densities of about twice that of nuclear matter, but that at higher densities the theory would be poor as a result of higher clusters becoming important.

For condensed matter systems, like the helium liquids, it was argued that the wound in the wave function was larger, about 0.3 for liquid ^{3}He (Østgaard 1968), and that therefore a cluster expansion would be less reliable than for nuclear matter. This was a consequence of the much stronger repulsive core of atomic potentials, which are represented by exponentials, or high inverse powers of the separation, as in the Lennard–Jones 6–12 potential. With a few exceptions, microscopic calculations of the ground state and low excited states of helium liquids were based on the Rayleigh–Ritz variational principle, and an account of these methods as of the late 1960s is given in Feenberg's book (1969).

At the time there was little contact between people working on nuclear problems and those working on liquid helium. This was due in part to the difference in methods described above, but also to the fact that interactions between nucleons are more complicated than those between atoms in condensed matter. Nuclear potentials have important tensor and spin-orbit contributions, while interactions in helium are well represented by a central potential which depends only on the separation of the atoms. Also, while the energy of helium atoms may be written to a good approximation as a sum of interactions between pairs of particles, this was known not to be the case for nuclear forces, which contain important three- and higher-body terms. (These take into account the deviation of the basic expression for the interaction hamiltonian from a sum over pairs of interacting particles, and must be distinguished from the effects of higher-order clusters mentioned above.)

With the identification of pulsars as neutron stars, physicists were confronted with the task of understanding the properties of nuclear matter at densities well in excess of ones at which it was thought the Brueckner–Bethe–Goldstone theory could be applied. An added complication was that matter in neutron stars has a ratio of neutrons to protons much greater than in terrestrial nuclei, and there is little empirical information available on matter with such high neutron excesses. This challenge led to a coming together of the two communities working on condensed matter problems and on nuclear problems. This may be exemplified by the paper of Pandharipande & Bethe (1973), in which the variational approach was developed for application to dense nuclear matter.

During the 1970s intense efforts were made to develop better calculational tools. At first it was not clear whether differences between the various microscopic calculations should be attributed to differences in the assumed interactions between nucleons, or to differences between the treatments of the quantum-mechanical many-body problem. Partly as a result of different groups agreeing to attack the same microscopic problem (Bethe's homework problem) with different theoretical approaches, systematic methods were developed for calculating the energy of quantum systems with known interactions. It turned out that the variational approach was rather well suited for calculating the energy of systems, but that the Brueckner–Bethe–Goldstone theory could also give reliable results for densities not much greater than nuclear saturation density, but at the expense of somewhat more labour. During this period the so-called Green's function Monte-Carlo method was being developed (see, for example, Schmidt & Ceperley 1991), and this gave a numerical technique for obtaining essentially exact solutions of the quantum mechanical many-body problem for simple potentials, thereby providing a reference with which the results of approximate techniques could be compared.

The situation today is that given a system of non-relativistic nucleons (or atoms) with specified interactions, one can calculate the energy of bulk matter and of the lightest finite nuclei (or clusters). The uncertainties in solving the many-body problem are in the nuclear case less than those in the input physics. Besides questions of the form of the interaction in such a model, as the density rises above that of nuclear matter one encounters increasingly the effects of relativity, and of non-nucleonic degrees of freedom, such as mesons, and higher mass baryons. At extreme densities quark and gluon degrees of freedom would be expected to dominate, but this may occur only at densities above those encountered in neutron stars. Even at densities as low as nuclear saturation density it is difficult at present to make reliable predictions of the finer aspects of correlations which signal a phase transition such as that to a superconducting or superfluid state.

In addition to providing a stimulus to understanding quantum liquids from a unified point of view, the discovery of neutron stars also gave impetus to attempts to understand nuclear phenomena over a much broader range of neutron-to-proton ratios. Terrestrial nuclei, the province of traditional nuclear physics, have roughly equal numbers of neutrons and protons, and only in extreme cases is the proton fraction less than 40%. However, in neutron stars the equilibrium proton fraction falls with increasing density, and when the average matter density reaches that of nuclear matter, the proton fraction may be as low as 10% or less. Expressed in terms of the standard neutron excess parameter, $\delta = (N-Z)/(N+Z)$, where N is the number of neutrons in a nucleus and Z the number of protons, nuclei in the laboratory have neutron excesses that rarely exceed $\frac{1}{4}$, while matter in neutron stars can have a neutron excess close to unity. The standard approach to calculating the properties of neutron-rich nuclei is to use a nuclear model to extrapolate from the properties of known nuclei. For neutron stars, an extrapolation of δ by a factor 4 is highly questionable. To avoid this problem, techniques were developed to describe the properties of dense matter over a wide range of neutron excesses and densities by combining information from known nuclei, for small neutron excesses, with the results of theoretical studies of matter with neutron excesses close to unity. This illustrates the way in which the discovery of pulsars challenged physicists to strive for a unified understanding of physical phenomena over a much broader range of conditions than those encountered in the laboratory, and not to be content with more limited explanations.

Another facet of the physics of neutron star interiors is that it involves aspects of many different subfields of physics. For example, in terrestrial matter solid-state energy scales, typically of order electronvolts, are very different from nuclear energy scales, which are of the order of megaelectronvolts. Consequently it is not generally necessary to consider solid-state and nuclear effects simultaneously. However, as a consequence of the smaller interparticle spacing, solid-state energies in dense matter can be of a magnitude comparable with nuclear energies, and it is necessary to consider solid-state and nuclear effects together. This interplay of solid-state and nuclear phenomena leads to, among other things, the rod-like and plate-like nuclear shapes expected to exist in matter at densities just below that of nuclear matter (Ravenhall *et al.* 1983; Williams & Koonin 1985; Lassaut *et al.* 1987; Lorenz *et al.* 1992). A second example is the physics of the liquid interior of neutron stars, where concepts developed for laboratory quantum liquids and metallic superconductors have been used together with aspects of nuclear physics. A further example is that in the context of the properties of matter at densities much above nuclear density, one must draw on insights from particle physics and nuclear physics.

To summarize, in trying to account for the impact the discovery of pulsars had on physics one can trace a number of threads. First, the existence of neutron stars challenged physicists to understand phenomena under conditions quite different from those in the laboratory, and it thereby enabled them to broaden a viewpoint that otherwise was focused rather narrowly on terrestrial conditions. Second, the problems posed were neither trivial, on the one hand, nor impossible, on the other. Laboratory physics provided some relevant information, but progress could be made only by combining this with theoretical studies. Third, the problems were intellectually stimulating because they had to be attacked by using ideas from several different subfields of physics. During the past 25 years significant progress has been made in understanding neutron star interiors, but there are still many basic questions that remain unanswered, as we shall illustrate in the following survey of some topical problems.

2. Contemporary themes

(*a*) *Equation of state*

Central to calculations of neutron star properties is the equation of state of dense matter. This determines the possible mass range for neutron stars, as well as their mass–radius relationship. In addition it has an important influence on questions such as how thick the crust of a neutron star is, and therefore it affects the cooling of neutron stars. As we mentioned above, over the past 20 years enormous strides have been taken in solving the many-body problem, and today the major uncertainties about neutron star structure are a consequence of limitations on our understanding of aspects of the interactions among nucleons. Information about the two-body interaction may be obtained from scattering experiments, and some clues about many-body interactions may be obtained by studies of the binding energies of very light nuclei and nuclear matter. However, this is insufficient to enable one unambiguously to pin down the interaction. In high-density matter the short-range parts of the interaction play an important role, and these cannot easily be determined from scattering data. Studies of nuclei are of little direct value for making extrapolations to matter at densities well above nuclear density because aspects of the interactions among nucleons that are relatively insignificant at nuclear densities become dominant at the densities of typical neutron star interiors.

Another aspect of nuclear interactions in need of clarification is the nature of three- and higher-body contributions. At large separations the most important process contributing to the three-body interaction is the one illustrated diagrammatically in figure 1*a*. Two nucleons interact by exchange of a pion, and one of the nucleons

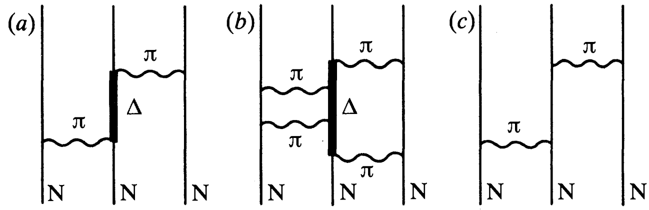

Figure 1. Perturbation theory diagrams for three-body effects: (*a*) the long-range part of the three-body interaction; (*b*) a contribution to the short-range part of the three-body interaction; (*c*) a contribution to three-body correlations resulting from the two-body interaction acting twice.

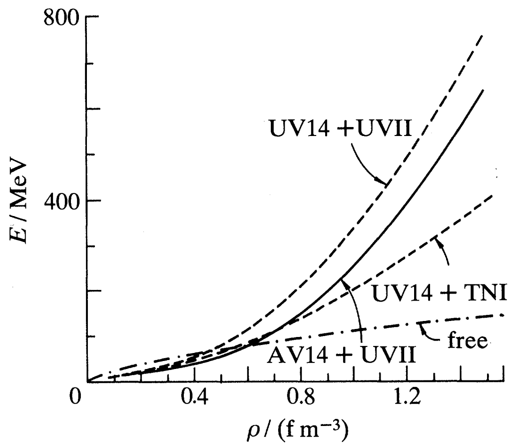

Figure 2. The energy per baryon of neutron matter as a function of baryon density ρ, for a free neutron gas, and for the interacting systems considered by Wiringa *et al.* (1988).

becomes a Δ, an excited state of the nucleon. Subsequently the Δ de-excites by exchanging another pion with a third nucleon. This process must be distinguished from that shown in figure 1*c*, which represents the one-pion-exchange interaction occurring twice, with only nucleons in the intermediate state. The latter process corresponds to treating the one-pion-exchange process, one of the contributions to the two-body interaction, in second order perturbation theory. It creates three-body correlations, but it does not give rise to an intrinsic three-body interaction since the intermediate state contains only nucleons. At shorter distances other contributions to the three-body interaction, such as that shown in figure 1*b*, become significant.

To illustrate these points we show in figure 2 the energy per particle of pure neutrons as a function of density. We give results for the free neutron gas, and for different choices of the two- and higher-body interactions, as calculated by Wiringa *et al.* (1988). The two-body interactions used, referred to as Argonne V14 (AV14) and Urbana V14 (UV14) both give good fits to scattering data, but differ in the short-range part of the tensor force. The potential referred to as UVII is a three-body interaction that has a form based on the diagrams shown in figure 1, with strengths adjusted to fit the binding energies of ^{3}He and ^{4}He and the saturation density and binding energy of charge-symmetric nuclear matter. The earlier results referred to as TNI include, less completely, some effects of the three-nucleon interaction. The first important point to notice is that for densities ρ expected in neutron stars with a mass of $1.4M_{\odot}$, ρ less than about $3\rho_s$–$4\rho_s$, where $\rho_s = 0.16\ \text{fm}^{-3}$ is the saturation density of nuclear matter, the total energy per particle differs from that of a free neutron gas by an amount that is small compared with the neutron mass. This gives some confidence that the basic model, non-relativistic nucleons with potential interactions, is a reasonable starting point. A second point is that the energy per particle is significantly different for different choices of the two-body interaction, and for different choices of the three- and higher-body interactions. A third remark is that for neutron star structure the pressure of the matter is an important function. It is proportional to the slope of the $E(\rho)$ curve, and one can see that while total energies for models that include interactions are not so different from that of a free neutron gas, pressures are generally much greater than that of the free gas.

(b) *Composition*

In recent years it has been realized that details of the composition of dense matter are more important than had been appreciated. Some neutrino-emitting processes are extremely sensitive to the presence of small or even minute quantities of minor constituents, such as protons, hyperons and isobars. Consequently the composition influences strongly the cooling of neutron stars. For the past decade or more the general view was that if neutron stars were made up primarily of nucleons, because of the low proton fraction neutrino emission would proceed via the modified Urca process. The reactions

$$\mathrm{n}+\mathrm{n}\rightarrow\mathrm{n}+\mathrm{p}+\mathrm{e}+\bar{\nu}_{\mathrm{e}} \tag{1}$$

and

$$\mathrm{n}+\mathrm{p}+\mathrm{e}\rightarrow\mathrm{n}+\mathrm{n}+\nu_{\mathrm{e}}, \tag{2}$$

would occur at equal rates, and neutron stars would cool slowly, with a characteristic timescale of order (1 year)/T_9^6. Here T_9 is the temperature in units of 10^9 K. On the other hand, if matter were in an exotic state, such as a Bose condensation of π or K mesons, or quark matter, more rapid neutrino emission processes could occur, and the characteristic timescale for cooling would be ≈ (1 min)/T_9^4. Recent studies (Boguta 1981; Lattimer *et al.* 1991; Prakash *et al.* 1992) have drawn attention to the fact that there are several simple processes that could give rapid cooling. (For a brief review of cooling, see Pethick (1992).)

The first of these is the so-called direct Urca process for nucleons, for which the basic reactions are neutron beta decay and electron capture on protons:

$$\mathrm{n}\rightarrow\mathrm{p}+\mathrm{e}+\bar{\nu}_{\mathrm{e}} \tag{3}$$

and

$$\mathrm{p}+\mathrm{e}\rightarrow\mathrm{n}+\nu_{\mathrm{e}}. \tag{4}$$

In the 1960s, when neutrino emission from neutron stars was first studied these processes were thought not to take place because of the impossibility of satisfying both energy and momentum conservation. Of course, the processes (3) and (4) are well known to take place in the laboratory, but conditions in neutron stars are very different. The argument was that for most of the life of a neutron star, matter in its interior is degenerate. Typical Fermi energies are of the order of 100 MeV, which corresponds to Fermi temperatures of about 10^{12} K, while the temperature of the matter is never this high even just after formation, and is generally many orders of magnitude lower. The condition for matter to be in beta equilibrium is

$$\mu_{\mathrm{n}} = \mu_{\mathrm{p}} + \mu_{\mathrm{e}}, \tag{5}$$

where μ_i is the chemical potential of species i, that is the energy of a particle at its Fermi surface. This implies that a neutron can be converted into a proton and a

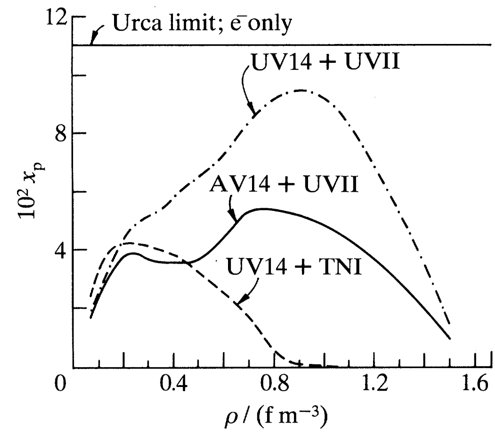

Figure 3. The proton fraction x_p of neutron-star matter in beta equilibrium with no neutrinos, as a function of baryon density ρ, as calculated by Wiringa *et al.* (1988). In the calculations illustrated, matter is assumed to consist of only neutrons, protons and electrons.

neutron (plus an antineutrino that carries no energy) at no cost in energy. The Pauli principle prohibits creating electrons or protons in states well below the Fermi surfaces because these are all occupied in a degenerate system. What this implies is that electrons, protons and neutrons that participate in reactions (3) and (4) must occupy states close to their respective Fermi surfaces, or equivalently that their momenta must lie close to the Fermi momentum. The condition for energy conservation in the reaction (3) can be satisfied if a neutron in a state just above the Fermi surface decays into an electron and a proton in partly occupied states close to their respective Fermi surfaces. The energy available to the neutrino or antineutrino is at most $\approx k_B T$, and therefore its momentum is $\approx k_B T/c$, which is negligible compared with the Fermi momenta. With the neglect of finite temperature effects, the condition for momentum conservation is thus

$$\boldsymbol{p}_n = \boldsymbol{p}_e + \boldsymbol{p}_p, \tag{6}$$

where the momenta must have magnitudes equal to the Fermi momenta, p_i. For this to be possible, the triangle inequality

$$p_n \leqslant p_e + p_p \tag{7}$$

must be satisfied. If the electrons and protons are the only charged constituents, the condition of charge neutrality ensures that their Fermi momenta must be equal, since the number density of a Fermi varies as p_i^3, and is independent of the mass. Thus for energy and momentum conservation to be possible in the direct Urca process, one must have $p_p \geqslant \frac{1}{2} p_n$, which is equivalent to $\rho_p \geqslant \frac{1}{8}\rho_n$. The proton fraction must therefore exceed $\frac{1}{9}$ for the direct Urca process to proceed. Estimates allowing for other possible constituents such as muons give similar, but somewhat larger, threshold proton fractions.

A noteworthy feature of the direct Urca reaction is that its rate jumps essentially discontinuously from zero to a finite value as the proton concentration passes the threshold value. As a consequence, neutrino emission rates can be extremely sensitive to the composition of matter.

In figure 3 we show the proton fraction of the matter, calculated assuming that neutrons, protons and electrons are the only constituents (Wiringa *et al.* 1988). The abbreviations used for the interactions are the same as earlier. These calculations exhibit just how sensitive the proton fraction is to the choice of interaction. For the models shown here, the proton fraction never reaches the threshold value of $\frac{1}{9}$ for the direct Urca reaction to occur, but it comes very close, and it might well exceed it in future models. The proton concentration depends on the energy difference between a neutron and a proton, and it is therefore related to the nuclear symmetry energy, which in turn is determined by the isospin dependence of the nuclear interactions.

Another minority constituent that can give rise to neutrino emission is the Λ hyperon, which can participate in the reactions

$$\Lambda \rightarrow \mathrm{p}+\mathrm{e}+\bar{\nu}_{\mathrm{e}} \tag{8}$$

and

$$\mathrm{p}+\mathrm{e} \rightarrow \Lambda+\nu_{\mathrm{e}}. \tag{9}$$

For low concentrations of Λs, the important triangle inequality to be satisfied is $p_{\Lambda} \geqslant |p_{\mathrm{e}}-p_{\mathrm{p}}|$, where p_{Λ} is the Fermi momentum of the Λ. Thus if matter had equal densities of electrons and protons, these processes could occur even for an infinitesimal concentration of Λs. When other constituents are allowed for, the threshold Λ concentration is found to be of order 10^{-3}.

The characteristic neutrino emissivity from the Λ direct Urca process is somewhat smaller than that of a nuclear process, since the process involves a change of strangeness and therefore the weak-interaction matrix element contains a factor $\sin\theta_{\mathrm{C}} \approx 0.2$, where θ_{C} is the Cabibbo angle. The characteristic cooling time is of order $1/\sin^2\theta_{\mathrm{C}}$ longer than that for the direct Urca process, but still very much shorter than for the modified Urca process.

For it to be energetically favourable to have Λ hyperons in dense matter, the energy of a Λ must be less than the sum of the proton and electron chemical potentials, which for matter in beta equilibrium is equal to the neutron chemical potential. If this were not the case Λs could decay into protons and electrons by the process (8). Estimates of Λ concentrations are very dependent on the interactions between Λs and nucleons, about which rather scanty information can be obtained from experiment. We note, however, that there is experimental evidence for three- or higher-body interactions among hyperons and nucleons, since experimental data on the binding energy of hypernuclei and on hyperon-nucleon scattering cannot be understood in terms of two-body interactions alone (Bodmer *et al.* 1984).

The recent work on neutrino emission has given added impetus to attempts to understand interactions among nucleons and hyperons, and thereby to determine more precisely the composition of dense matter.

(c) *Neutron-rich nuclei and the spin-orbit interaction*

We turn now to some problems related to matter at relatively low densities by neutron star standards. At low densities matter in its ground state is rather similar to terrestrial matter and consists of nuclei immersed in a sea of electrons. At a density of about 4×10^{11} g cm^{-3}, roughly a thousandth of nuclear matter density, nuclei become so neutron-rich that neutrons begin to 'drip' out of nuclei, and matter consists of nuclei immersed in a sea of neutrons as well as a sea of electrons. The question we wish to address is which nuclei are energetically favourable at densities below neutron drip.

Early calculations (Baym *et al.* 1971) were based on the Bethe–Weizsäcker semi-empirical mass formula, with parameters obtained from fits to laboratory nuclei. They led to the conclusion that nuclei with closed neutron shells, especially the $N = 82$ shell, would be the equilibrium ones. Not very long ago Haensel *et al.* (1988) performed calculations of equilibrium nuclei using the Hartree–Fock–Bogoliubov (HFB) method, a mean-field approach that allows for pairing effects. In this method, data about ordinary nuclei is distilled into a microscopic hamiltonian, which is then used to calculate properties of nuclei that cannot be measured directly. This method of calculating nuclear properties would be expected to be more reliable than direct extrapolation of nuclear properties based on the semi-empirical mass formula. The surprising conclusion of this work was that just below neutron drip, proton shell effects (rather than the neutron ones, as in the earlier calculations) appear to dominate. Another surprising result was that nuclei with 40 protons appear to be particularly stable.

This work poses a number of questions. First, why do proton shells dominate, and second, why $Z = 40$, rather than $Z = 50$ as found in laboratory nuclei? The reason that neutron shell effects become less pronounced for nuclei close to neutron drip is presumably that the most energetic occupied neutron levels lie close to the continuum. As to the second question, there are two points that need to be clarified: is the stability of nuclei with $Z = 40$ in the HFB approximation a real shell effect, or is it due to a rather small shell energy difference between two shells that happens to be sufficient to favour $Z = 40$ nuclei? To address the latter point one should carry out HFB calculations for a wide range of nuclei, and analyse the shell effects. A more fundamental question concerns the strength of the spin-orbit force in neutron-rich nuclei. Taken at face value, a $Z = 40$ closed shell would appear to indicate a weakening of the spin-orbit interaction in neutron-rich nuclei, because $Z = 40$ corresponds to filling the 1s, 1p, 2s–1d and 2p–1f shells. For ordinary nuclei the closed shell occurs at $Z = 50$ because the $1g_{9/2}$ level is brought down from the next shell by the spin-orbit interaction.

The nature of shell effects in neutron-rich nuclei is important in the context of the astrophysical r-process (Cowan *et al.* 1991), in which heavy elements are built up by rapid capture of neutrons. In the traditional view, peaks in nuclear abundances are associated with neutron closed shells at $N = 82$ and $N = 126$. This provides added motivation for working towards a better understanding of shell effects, and there has been progress on this problem, as we shall now describe.

The majority of nuclear models used for systematic calculation of nuclear masses for a wide range of neutron and proton numbers are based on mean-field concepts, and parameters in the model are obtained by fitting to known nuclei. In the case of the spin-orbit interaction one has to assume some particular form for it, even though one does not have a thorough microscopic understanding of its origin. A recent advance relevant to this problem is that techniques for solving the quantum mechanical many-body problem, which we discussed in the first part of the article, have been developed, so that it is now possible to make reliable calculations of energies of light nuclei other than the deuteron, the triton, ^{3}He and ^{4}He, starting from a microscopic hamiltonian. One application has been to the spin-orbit splitting of ^{15}N. The calculations of Pieper *et al.* (1992) account very well for the measured $1p_{3/2}$–$1p_{1/2}$ splitting of 6.3 MeV. What is surprising is that the two-body nucleon–nucleon interaction treated with two-body correlations accounts for less than half of the total splitting, with the remainder coming roughly equally from higher-order correlation effects with the two-body interaction, and from three-nucleon inter-

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actions. The fact that theory and experiment agree so well increases one's confidence in the nuclear interactions used, as well as the many-body theory techniques. It would be valuable to calculate spin-orbit splittings for neutron-rich nuclei, since this would make possible the construction of better spin-orbit interactions for incorporation in nuclear models of the mean-field type, enabling one to make improved estimates of the masses of neutron-rich nuclei. The anticipated development in the coming years of experimental facilities using radioactive beams (Boyd & Tanihata 1992) will produce data on nuclei near the neutron and proton drip lines, and thus produce an invaluable anchor for this end of the investigation.

This example illustrates the close connections between neutron-star problems and those in other areas of physics. It also brings out the fact that information of importance for neutron-star physics may be obtained from unexpected sources. We have described above just how important the three- and higher-body interactions are for the properties of matter at densities well above nuclear density, but it comes as a surprise that the same interaction plays such an important part in determining the spin-orbit splitting at nuclear densities.

3. Concluding remarks

The topics we have discussed illustrate the continuing interplay between observations of neutron stars and physical studies. The existence of neutron stars has had a decisive influence on maintaining the study of dense matter as one of the central and most active areas of nuclear physics. There are, however, many other areas where the existence of neutron stars, and observations of them, have been a powerful stimulus to thinking and speculation. At the highest densities, an interesting question is whether the ground state of matter is better regarded as a system of interacting quarks, rather than nucleons. This is a difficult question, because there are large uncertainties in the equation of state for quark matter, as well as uncertainties we have already mentioned for matter made up of nucleons. The nature of the transition between matter made up of nucleons and quark matter is not understood at all well, so it is impossible at present to make definitive statements about whether or not quark matter can exist in the central regions of neutron stars. A topic that has received much attention is superfluidity of neutrons and superconductivity of protons, which play important roles in a number of theories of glitch behaviour in pulsars (Pines 1991; Baym & Epstein 1992). The strong magnetic fields (up to 10^{13} G) at the surfaces of neutron stars has opened up the study of condensed matter physics and atomic physics in a quite new régime. Yet another topic is the use of neutron stars to improve constraints on novel particles (Raffelt 1990).

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