Tensor correlations and P-wave pairing in neutron matter

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Landau-Fermi liquid theory is a powerful effective theory for strongly interacting Fermi systems at low temperatures. It has been successfully applied to liquid ^{3}He, nuclear matter and nuclei. However, in contrast to the interaction between ^{3}He atoms, nuclear forces are complicated due to the large non-central spin-orbit and tensor components. Here, we report on the in-medium modification of the effective nucleon-nucleon interaction, paying particular attention to spin-dependent forces [1].

The form of the two-body interaction in vacuum is constrained by symmetries. In particular, in non-relativistic theories, Galilean invariance implies that the two-body interaction is independent of the particle-pair (cm) momentum $\mathbf{P} \equiv \mathbf{p}_1 + \mathbf{p}_2 = \mathbf{p}_3 + \mathbf{p}_4$. In this case, the possible operators are scalar, spin-spin, spin-orbit, tensor and quadratic spin-orbit forces. In the medium, the Fermi sea defines a preferred frame, and the effective two-body interaction depends on the cm momentum. On the Fermi surface, this leads to novel non-central forces of the form

$$S_{12}(\mathbf{P}) \qquad \text{cm tensor} \qquad (1)$$

$$D_{12}(\mathbf{q},\mathbf{P}) \equiv i(\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2)\cdot\mathbf{q}\times\mathbf{P} \qquad \text{diff vector} \qquad (2)$$

$$A_{12}(\mathbf{q}',\mathbf{P}) \equiv (\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2)\cdot(\mathbf{q}'\times\mathbf{P}) \qquad \text{cross vector,} \qquad (3)$$

with $\mathbf{q} \equiv \mathbf{p}_1 - \mathbf{p}_3$ and $\mathbf{q}' \equiv \mathbf{p}_1 - \mathbf{p}_4$. The antisymmetric operators D_{12} and A_{12} do not conserve the spin of the particle pair. Both cm tensor and A_{12} survive in the Landau ($q \to 0$) limit and lead to novel Fermi liquid parameters.

In [1], we have studied the microscopic origin of these interactions. We have also computed particle-particle, hole-hole (pp/hh) and particle-hole (ph) contributions to the quasiparticle interaction and scattering amplitude to second order in the low-momentum interaction $V_{\text{low}\,k}$ [2]. It is well-known that the second-order tensor force is important for nuclear binding, since the spin-recoupling of iterated tensor operators gives a large contribution to the scalar interaction. Similar recoupling arguments imply that the interference of the large spin-spin part ($G_0 \approx 0.6 - 0.8$ in neutron matter) with the tensor force in the ph channels leads to a substantial renormalization of the tensor interaction [3]. (Similarly, we also find a significant renormalization of the spin-orbit force; this leads to the suppression of P-wave pairing discussed below.) Moreover, the presence of a third particle in intermediate states induces novel contributions, which give rise to a particular coupling between the spin and the angular motion and leads to antisymmetric spin operators. The cm tensor emanates from both pp/hh and ph diagrams. There are also kinematical (boost) corrections to D_{12} and A_{12} [4], which however are relatively small (of order $k_{\rm F}^2/m^2$).

We find a substantial renormalization of the exchange tensor $S_{12}(\mathbf{q}')$ as well as significant contributions to the cm tensor. This implies that higher-order calculations, e.g., within the RG approach [3], are needed. We also explore the effect of particle-hole screening on the ^{3}P$_2$ pairing gap in neutron star interiors. As for the S-wave gaps [3], large effects are expected. In weak coupling BCS theory, neglecting the coupling to the ^{3}F$_2$ channel, $\Delta_{^3\mathrm{P}_2} = k_{\rm F}^2/m \, \exp\bigl[\pi/\bigl(2\,k_{\rm F}\,m\,V_{\text{pairing};{}^3\mathrm{P}_2}\bigr)\bigr]$. As shown in Fig. 1, the in-medium modification of the spin-orbit force leads to a significant reduction of the ^{3}P$_2$ gap. Note that when only central induced forces are included (dotted vs. dashed line), the gap is increased [6]. Neutron star cooling calculations require P-wave gaps below $\Delta \lesssim 30\,\text{keV}$ [7].

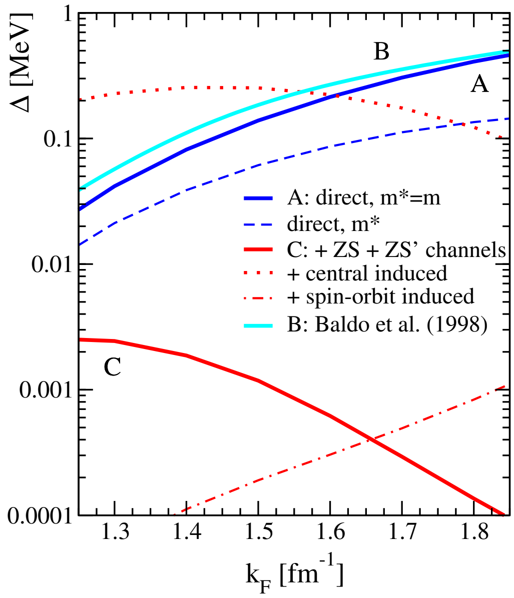

Figure 1: The angle-averaged gap $\Delta_{^3\mathrm{P}_2}$ versus Fermi momentum in neutron matter. The direct ($V_{\text{low}k}$) and the pairing gap including polarization effects on the pairing interaction are shown (with only induced central, only induced spin-orbit or total to second-order). For reference, we give the results of Baldo *et al.* [5], obtained by solving the coupled channel BCS equation for different potentials.

Implications of the new interactions for nuclear spectra, for spin-isospin response and neutrino transport in supernovae, for spin-polarized systems, spin relaxation, mixing of spin and density waves, and for scattering with polarized beams remain to be investigated.

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