Short-range correlations in asymmetric nuclear matter

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Abstract

The spectral function of protons in the asymmetric nuclear matter is calculated in the self-consistent $T$-matrix approach. The spectral function per proton increases with increasing asymmetry. This effect and the density dependence of the spectral function partially explain the observed increase of the spectral function with the mass number of the target nuclei in electron scattering experiments.

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The hard core in the free nucleon-nucleon potential induces strong short-range correlations in the nuclear medium. The inclusion of these correlations in the modeling of the nuclear medium is crucial. Variational, Brueckner-Hartree-Fock, and self-consistent $T$-matrix nuclear matter calculations take this effect into account. As a result of the scattering in the medium nucleonic excitations get dressed. A measure of such medium modifications is given by the spectral function, which can be observed in electron scattering experiments. The extraction of the spectral function is relatively straightforward in the Plane Wave Impulse Approximation but important final state rescattering effects complicate the analysis. The knowledge of the spectral function sheds light on the origin of the nuclear binding energy and gives the nucleon momentum distribution.

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Several calculation of the spectral function exists, both for finite systems \[15, 16\] and for nuclear matter \[17, 19, 18, 19\]. At high momentum and high removal energy the spectral function is dominated by short-range correlations which can be studied in the homogeneous nuclear matter. Existing calculations are restricted to symmetric or pure neutron nuclear matter. On the other hand electron scattering experiments are performed on nuclei with a range of values of the neutron to proton ratio \(N/Z\). The scaled spectral function, i.e. the spectral function divided by the number of protons, was compared for different nuclei and a significant increase with the mass number was observed \[20\]. This is interpreted as an indication of strong short-range correlations due to neutron-proton scattering which populates the spectral function at high removal energy \[21\]. In this work we present the first calculation of the proton spectral function in the asymmetric nuclear matter. We discuss the effect of the \(N/Z\) ratio on the scaled spectral function for different atomic number of the target nuclei.

The calculation is performed in the self-consistent \(T\)-matrix \[22\] approach using fermion propagators dressed in the self-consistent self-energy. The scheme is thermodynamically consistent and the obtained single particle properties, i.e. the self-energy and the spectral function are consistent with the global properties such as the binding energy \[14\]. In the Brueckner approach the spectral function can be reliably calculated only after inclusion of the rearrangement terms \[18\]. The self-consistent in medium \(T\)-matrix \[23, 11, 10, 24, 14\] is

\[
T = V + VGGT
\]

where the Green’s functions \(G^{-1} = \omega - p^2/2m - \Sigma\) in the ladder propagator are dressed by the self-consistent self-energy

\[
i\Sigma = Tr[TG].
\]

The details of the calculation can be found in Refs. \[19, 25\]. The same retarded self-energy \(\Sigma\) is used to construct the spectral function

\[
A(p, \omega) = -2\text{Im}G(p, \omega) = \frac{-2\text{Im}\Sigma(p, \omega)}{\left(\omega - p^2/2m - \text{Re}\Sigma(p, \omega) + \mu\right)^2 + \text{Im}\Sigma(p, \omega)^2}.
\]

The calculation is done for a range of densities and asymmetries using the CD-Bonn
potential. The hole spectral function \( A^h(p, E) = A(p, -E) \) is shown in Fig. 1 as a function of the missing energy for several values of the momentum. The spectral function at normal nuclear density is presented for a symmetric nuclear matter and for \( Z/N = 0.7 \). The proton spectral function is larger for the symmetric nuclear matter, but at large missing energy the two curves almost coincide. Since in the asymmetric medium a lower number of p-p collisions is compensated by a more frequent n-p collisions contribution, tensor interaction would lead to a higher scattering rate for high momentum on-shell protons in the asymmetric medium. A far off-shell proton however is scattered in a similar manner in the symmetric and asymmetric nuclear matter. In fact \( |Im \Sigma(p, \omega)| \) for protons far off-shell \( (\omega < \mu, p > p_F) \) is even slightly smaller in the asymmetric than in the symmetric nuclear matter. Far off-shell the value of the spectral function is determined by the imaginary part of the self-energy in the numerator of Eq. 3 and leads to almost no variation of the hole spectral function with asymmetry. Only for energies closer to the quasi-particle pole \( (p > p_F, \omega > \mu) \) is the scattering of protons larger in the asymmetric nuclear matter, giving a higher on-shell width for high momentum protons in the neutron rich nuclear matter.

When comparing different proton densities in the asymmetric nuclear matter the scaled spectral function \( \frac{N+Z}{2Z} A^h(p, \omega) \) is used, which is a measure of the spectral function per proton. We see that the high energy and high momentum part of the scaled hole spectral function is larger in the asymmetric nuclear matter. The increase of the far off-shell correlations per proton compensates the slight decrease of the proton off-shell scattering rate.

The real-part of the self-energy and the quasiparticle poles depend on the neutron to proton ratio. Accordingly the proton Fermi momentum depends on the proton density, which changes with the proton content. In Fig. 2 is plotted the proton momentum distribution

\[
 n(p) = \int \frac{dE}{2\pi} A^h(p, E) .
\]  

(4)
in nuclear matter at normal density for different \( Z/N \) ratios. The depletion of the occupation number inside the Fermi sphere and the high momentum component in the distribution are given by short-range correlations in the medium. These effects to within
a few percent are the same for the proton to neutron ratio changing from 1 to 0.7. The change in the proton density with asymmetry is accommodated by a shift in the proton Fermi momentum.

Experiments with electron scattering on finite nuclei are available for several target masses (C, Al, Fe and Au) [20]. A strong dependence on the target of the scaled proton spectral function was interpreted partly as a signal of strong p-n correlations. The increase of the off-shell hole spectral function per proton when going from C to Au target is about a factor 2. The spectral function at high missing energy and momentum can be calculated using the local density approximation

\[ S(p, E) = \frac{2}{(2\pi)^4} \int d^3r A_h^h(p, E, \rho(r)) . \]  

In Fig. 3 is plotted the spectral function divided by the number of protons for several nuclei. The spectral function depends on the mass number of the target. Part of the increase of the spectral function at high missing energy is due to the different proton to neutron ratio. We have

\[ S(p, E) \propto \text{Volume } A_h(p, E) = \frac{Z}{\bar{\rho}_p} A_h(p, E) \]  

where $\bar{\rho}_p$ is the mean proton density. The scaled spectral function is

\[ \frac{S(p, E)}{Z} \propto \frac{1}{\bar{\rho}_p} A_h(p, E) = \frac{1}{\bar{\rho}} \frac{N + Z}{Z} A_h(p, E) . \]

Since the hole spectral functions $A_h(p, E)$ at different proton densities are very similar in the considered region of energy and momentum (Fig. 1) we see from Eq. 7 that the scaled proton spectral function $S(p, E)/Z$ increases with the asymmetry for nuclei with the same average density $\bar{\rho}$. This effect however is not sufficient to explain quantitatively the observed dependence on the target mass.

The upper curves in Fig. 3 are the spectral functions without dividing by $Z$, i.e. the lower curves multiplied by $12Z/A$. In a homogeneous matter this rescaling should bring the curves back onto each other as in Fig 1. The remaining difference visible in Fig. 3 is due to the density dependence of the spectral function. Heavier nuclei have a larger mean density which gives rise to stronger short-range correlations. Qualitatively the same effect is seen in the data [20], but the strongest increase of the proton spectral function
happens between Fe and Au targets, and the effect is much more pronounced, especially in the region where the Δ resonance starts to be visible.

The proton spectral function in the asymmetric nuclear matter is calculated. In the far off-shell region the spectral function does not depend strongly on the proton-neutron asymmetry. It means that the spectral function scaled by the proton number is approximately inversely proportional to the proton density (7). This effect together with density dependence of the spectral function leads to an increase of the scaled proton spectral function with increasing mass number of the target. The experimentally observed increase of the spectral function for heavy target nuclei is stronger than our estimate, especially for the case of gold. Larger frequency of neutron-proton interactions in asymmetric matter leads to a stronger scattering of proton excitation on-shell, but in the off-shell region \((p > p_F, \omega < \mu)\) we find that the scattering width \(2|\text{Im}\Sigma(p,\omega)|\) decreases slightly with the asymmetry.

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Figure 1: The hole spectral function in the asymmetric nuclear matter at normal nuclear density. The lines correspond from top to bottom to \( p = 255, 330, 410, 500, 570, 650 \) MeV. The solid lines are for \( N = Z \) and the dashed lines for \( Z/N = 0.7 \). The dotted lines denote the proton spectral function scaled by the mass number to proton ratio \( \frac{N+Z}{2Z} \), giving a measure of the occupancy at a missing energy and momentum per proton.
Figure 2: The momentum distribution of protons in the nuclear matter at normal density. The solid line is for $N = Z$ and the dashed line for $Z/N = 0.7$. 
Figure 3: The hole spectral function scaled by the number of protons for Au, Fe, Al and C nuclei; solid, dashed, dotted, and dashed-dotted lines, respectively (lower curves). The upper curves are multiplied by $\frac{12Z}{A}$. The points represent the data from Ref. [20] in the region below the $\Delta$ resonance.