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Two-nucleon correlations and the structure of the nucleon spectral function at high values of momentum and removal energy

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The basic two-nucleon configurations which generate the structure of the nucleon spectral function at high values of momenta and removal energies are analyzed. A model spectral function expressed through a convolution integral of the momentum distributions describing the relative and center-of-mass motion of a correlated pair is suggested and shown to satisfactorily reproduce the spectral function of the three-body system and nuclear matter calculated in terms of realistic nucleon-nucleon interactions in a wide range of nucleon momenta and removal energies.

The scattering of various kinds of projectiles off nuclei at high values of momentum and energy transfer can provide unique information on both the fundamental hadronic interaction and the structure of nuclei.[1] In the former case, the nucleus is viewed as the hadronic medium which can induce quantum chromodynamical (QCD) effects which cannot be investigated on a free nucleon, whereas in the second case small components of the nuclear wave function [e.g., nucleon-nucleon (NN) correlations, exotic components, etc.], which hardly show up in low-energy scattering, could be investigated. In both cases, significant predictions of various effects and reliable interpretations of the experimental data do require a model for the nuclear wave function. It turns out that even at very high values of the momentum and energy transfer, the nucleus cannot be simply described as a collection of scattering centers subject only to Fermi motion, but the full nucleon dynamics generating the removal energy and momentum distributions of each nucleon has to be considered (see, e.g., Refs. 2–6). In processes at very high energies, when the final-state interaction of the knocked-out nucleon with the $(A-1)$ nucleon system is supposed to play a minor role, the cross section for inclusive and exclusive processes depends upon nuclear structure through the spectral function $P(k,E)$, which represents the joint probability to find in the target a nucleon with momentum k and removal energy E; since the latter is defined as $E=|E_A|-|E_{A-1}|+E_{A-1}^*$, where E_{A-1}^* represents the (positive) excitation energy of the system with $(A-1)$ nucleons measured with respect to its ground state, the spectral function also represents the probability that, after a nucleon is knocked out from the target, the final $(A-1)$ system is left with excitation energy E_{A-1}^*. Within the nonrelativistic Schrödinger description of nuclei, the spectral function is defined as follows (see, e.g., Ref. 4):

$$P(k,E)=\langle\Psi_A^0|a_{\mathbf{k}}^\dagger\delta[E-(H-E_A)]a_{\mathbf{k}}|\Psi_A^0\rangle=\sum_f|\langle\Psi_{A-1}^f|a_{\mathbf{k}}|\Psi_A^0\rangle|^2\delta[E-(E_{A-1}^f-E_A)]$$
$$=\frac{1}{(2\pi)^3}\sum_f\left|\int d\mathbf{r}\,e^{i\mathbf{k}\cdot\mathbf{r}}G_{f0}(\mathbf{r})\right|^2\delta[E-(E_{A-1}^f-E_A)]\,, \quad (1)$$

where $a_{\mathbf{k}}^\dagger(a_{\mathbf{k}})$ is the creation (annihilation) operator of a nucleon with momentum $\mathbf{k}$, H is the nuclear Hamiltonian and $G_{f0}(\mathbf{r})$ is the overlap integral between the intrinsic eigenfunction Ψ_A^0 (with eigenvalue E_A) of the ground state of the Hamiltonian H, and the eigenfunction Ψ_{A-1}^f (with eigenvalue $E_{A-1}^f=E_{A-1}+E_{A-1}^*$) of the state f of the Hamiltonian H_{A-1}.

For a noninteracting Fermi gas, one has

$$P^{(\mathrm{FG})}(k,E)=\frac{3}{4\pi k_F^3}\theta(k_F-k)\delta\left[E+\frac{k^2}{2M}\right], \quad (2)$$

whereas for a system of independent particles filling shell-model states α with momentum distribution n_α and single-particle energies ε_α, one has

$$P^{(\mathrm{SM})}(k,E)=\frac{1}{4\pi A}\sum_\alpha A_\alpha n_\alpha^{(\mathrm{SM})}(k)\delta(E+|\varepsilon_\alpha|)\,. \quad (3)$$

In Eq. (3) A is the total number of nucleons and A_α the number of nucleons in the state α ($A=\sum_\alpha A_\alpha$) and the sum over α runs only over hole states of the target, which means that $c_\alpha\equiv\int n_\alpha^{(\mathrm{SM})}(k)k^2dk=1$, for $\alpha<\alpha_F$, and 0 for $\alpha>\alpha_F$.

The main effect of NN correlations which are generated by the short range and tensor parts of realistic NN interactions is to deplete states below the Fermi sea and to make the states above the Fermi level partially occupied; by such a mechanism, high momentum and high removal energy components in $P(k,E)$ are generated. Disregarding the finite width of the states below the Fermi level, the spectral function which includes the effects of ground-state NN correlations can be represented in the following form:[2]

$$P(k,E)=P_0(k,E)+P_1(k,E) \tag{4}$$

where

$$P_0(k,E)=\frac{1}{(2\pi)^3}\sum_\alpha \left|\int d\mathbf{r}\, e^{i\mathbf{k}\cdot\mathbf{r}}G_\alpha(\mathbf{r})\right|^2 \delta(E+|\varepsilon_\alpha|)$$
$$=\frac{1}{4\pi A}\sum_\alpha A_\alpha n_\alpha(k)\delta(E+|\varepsilon_\alpha|) \tag{5}$$

represents the shell-model contribution, where NN correlations mainly manifest themselves in the depletion of the normally occupied states $[c_\alpha=\int n_\alpha(k)k^2dk<1]$, and

$$P_1(k,E)=\frac{1}{(2\pi)^3}\sum_{f\neq\alpha}\left|\int d\mathbf{r}\, e^{i\mathbf{k}\cdot\mathbf{r}}G_{f0}(\mathbf{r})\right|^2 \times\delta[E-(E^f_{A-1}-E_A)] \tag{6}$$

includes more complex configurations of the $(A-1)$ nucleon system, e.g., one-particle–two-hole states which can be reached when two-particle–two-hole states in the target nucleus are considered.

The calculation of the spectral function requires the solution of the Schrödinger equation for A and $(A-1)$ interacting nucleons, and therefore has been obtained, so far, only in the case of $A=3$ (Refs. 4 and 5) and nuclear matter.[6] It is the purpose of this paper to present a model spectral function which would hold for any value of A and could be used to correctly describe the high momentum and high removal energy components of a nucleon embedded in the nuclear medium. To begin with, let us recall several important quantities which are related to the spectral function, viz the momentum distribution

$$n(k)=4\pi\int P(k,E)dE\,, \tag{7}$$

the mean kinetic energy

$$\langle T\rangle=\int\frac{k^2}{2M}P(k,E)d\mathbf{k}dE=\int\frac{k^4}{2M}n(k)dk\,, \tag{8}$$

and the mean removal energy

$$\langle E\rangle=\int EP(k,E)d\mathbf{k}dE\,. \tag{9}$$

The last two quantities are related to the total energy per particle ε_A by the energy sum rule,[7]

$$\varepsilon_A=\tfrac{1}{2}\left[\frac{A-2}{A-1}\langle T\rangle-\langle E\rangle\right], \tag{10}$$

if the Hamiltonian contains only two-body forces.

Recent many-body calculations[4–6,8,9] have computed ε_A and $n(k)$ for a series of nuclei, so that the theoretical values of $\langle T\rangle$ and $\langle E\rangle$ for systems ranging from ^{3}He to nuclear matter are known. In constructing our model spectral function we will make use of the results of the calculations of $n(k)$ and $P(k,E)$ which show that: (i) because of NN correlations, the momentum distributions $n(k)$ for $k>2$ fm^{-1} are several orders of magnitude larger than the predictions from mean-field calculations and, moreover, apart from a scaling factor, they seem to be almost independent of the atomic weight A;[4,8,9] (ii) the momentum sum rule [Eq. (7)] can be saturated at high momenta only by extending the upper limit of integration to very high values of E ($E>50$ MeV), which clearly indicates the strong link between high momentum and high removal energy components of the nuclear wave function, both being determined by NN correlations.[4,6]

Both features should reflect some local properties of the NN wave function in the nuclear medium at short interparticle distances. On the basis of such an observation, and analyzing the perturbative expansion of both the NN interaction and the momentum distribution for potentials decreasing at large k as powers of k, it has been argued[1] that the spectral function at high values of k and E should be governed by ground-state configurations in which the high momentum $\mathbf{k}_1\equiv\mathbf{k}$ of a nucleon is balanced mainly by the momentum $\mathbf{k}_2\cong-\mathbf{k}$ of another nucleon, with the remaining $(A-2)$ nucleons acting as a spectator with momentum $\mathbf{k}_{A-2}\cong0$ (configurations corresponding to high values of $\mathbf{k}_{A-2}$ are ascribed, within such a naive picture, to three-nucleon correlations). Energy conservation would require that

$$E^*_{A-1}+E^R_{A-1}\cong\frac{k^2}{2M}\,, \tag{11}$$

where $E^R_{A-1}=k^2/2(A-1)M$ is the recoil energy of the $(A-1)$ nucleon system. If the momentum and the intrinsic excitation energy of the $(A-2)$ system are totally disregarded, the intrinsic excitation energy of the $(A-1)$ system would therefore be

$$E^*_{A-1}=\frac{(A-2)k^2}{2(A-1)M}\,. \tag{12}$$

Within such a picture, the spectral function $P_1(k,E)$ will have the following form:

$$P_1(k,E)\propto\delta[E-E_1(k)] \tag{13}$$

with

$$E_1(k)=E_{\rm thr}+\frac{(A-2)k^2}{2(A-1)M}\,, \tag{14}$$

where $E_{\rm thr}=|E_A|-|E_{A-2}|$ is the two-particle break-up threshold. The mean removal energy for a given k would then be

$$\langle E(k)\rangle=E_1(k)\,. \tag{15}$$

In what follows, such a model will be called the *naive two-nucleon correlation* model and will be referred to as 2NC. At high values of k and E, the calculated spectral functions for ^{3}He (Refs. 4 and 5) and nuclear matter[6] exhibit, indeed, for fixed values of k, broad peaks in E, whose width increases with k. [Note that in the rest of the paper the position of the peaks of a generic spectral function will be denoted by $E_1(k)$.] The purpose of this paper is twofold: (i) to show to what extent the 2NC model correctly predicts the position of the peaks of $P_1(k,E)$, and (ii) to understand the basic mechanism, not included in the 2NC model, which produces broad peaks of $P_1(k,E)$ instead of a δ-type shape. The answer to the first question is provided by Fig. 1, which shows an impressive agreement between the value of $\langle E(k)\rangle$ calculated with the spectral function and the prediction of the 2NC model. However, it can also be seen that the 2NC model cannot predict the difference between $\langle E(k)\rangle$ and $E_1(k)$ provided by many-body calculations. Moreover, the 2NC model, by definition, cannot provide values of the spectral function for $E \neq E_1(k)$. Let us therefore turn to the second objective, and try to understand what the NN correlation mechanism which produces a nonvanishing spectral function for $E \neq E_1(k)$ is and whether such a mechanism can also explain the difference between $E_1(k)$ and $\langle E(k)\rangle$ shown in Fig. 1.

To begin with, we consider the asymptotic behavior of the ground-state wave function Ψ_A^0 appearing in the overlap integral G_{f0}, in the case of potentials decreasing at large k as powers of k. To be more specific, we consider that the high momentum and the high removal energy parts of the spectral function are generated by such configurations in which two particles are very close and form a correlated pair, which, at the same time, are far apart from the other $(A-2)$ particles. Our assumption means that the two nucleons in the pair have large relative momenta, whereas the center-of-mass (c.m.) momentum of the pair is a low one, so that the c.m. wave function of the pair can be represented by an $l=0$ wave. If we specialize, for ease of presentation, to the three-nucleon system, one arrives, after some lengthy but straightforward algebra, to the following expression for the spectral function $P_1(k,E)$:[10]

$$P_1(k,E)=\int d\mathbf{k}_2 d\mathbf{k}_3\,\delta(\mathbf{k}+\mathbf{k}_2+\mathbf{k}_3)\,\delta\left[E-E_{\rm thr}-\frac{(\mathbf{k}_2-\mathbf{k}_3)^2}{4m}\right] n_{\rm rel}\left[\frac{|\mathbf{k}-\mathbf{k}_2|}{2}\right] n_{\rm c.m.}\left[\frac{|2\mathbf{k}_3-(\mathbf{k}+\mathbf{k}_2)|}{3}\right], \tag{16}$$

where the momenta $\mathbf{k}$, $\mathbf{k}_2$, and $\mathbf{k}_3$ are measured from the c.m. of the system, $n_{\rm c.m.}$ represents the momentum distribution of the c.m. of a proton-proton (p-p) or proton-neutron (p-n) pair with respect to the third nucleon, and $n_{\rm rel}$ is the momentum distribution of the relative motion of the two nucleons in the pair. By integrating over $\mathbf{k}_2$, one obtains

$$P_1(k,E)=\int d\mathbf{k}_3\,\delta\left[E-E_{\rm thr}-\frac{(\mathbf{k}+2\mathbf{k}_3)^2}{4m}\right] \times n_{\rm rel}(|\mathbf{k}+\tfrac{1}{2}\mathbf{k}_3|)\,n_{\rm c.m.}(|\mathbf{k}_3|)\,. \tag{17}$$

The calculation of the spectral function within the above expression requires, therefore, only the knowledge of the momentum distributions. Let us analyze some particular cases. The 2NC model [Eqs. (13) and (14)] is recovered by placing $n_{\rm c.m.}(\mathbf{k}_3)=\delta(\mathbf{k}_3)$, i.e., the spectator nucleon at rest. When the motion of the latter and the link between $\mathbf{k}$, $\mathbf{k}_3$, and E is considered, not only a spectral function in the whole range of variation of E ($E_{\rm thr}<E<\infty$) is generated, but a shift of the peak position from the values predicted by the 2NC model [Eq. (14)] is also obtained. Both the E dependence and the peak position of the spectral function are governed by the features of $n_{\rm c.m.}$ and $n_{\rm rel}$, whose calculation, unlike the case of the spectral function, requires the knowledge of the ground-state wave function only. A further integration of Eq. (17) over the angular variables of $\mathbf{k}_3$ yields

$$P_1(k,E)=\frac{2\pi M}{k}\int_{k_3^-}^{k_3^+} dk_3\,k_3\,n_{\rm rel}\left[\frac{3k^2+k_0^2-3k_3^2}{4}\right]^{1/2} \times n_{\rm c.m.}(k_3)\,, \tag{18}$$

where $k_3^{\pm}=|k\pm k_0|/2$ and $k_0=[4M(E-E_{\rm thr})]^{1/2}$. In Eqs. (17) and (18), $n_{\rm rel}$ refers to a proper spin and isospin combination of a p-p and p-n pairs in the continuum, and, correspondingly, $n_{\rm c.m.}$ represents the momentum distribution of a neutron (proton) with respect to the p-p (p-n) pair in the continuum. All these quantities have been calculated with realistic interactions either by variational[4] or Faddeev[5] approaches. As already pointed out, the three-nucleon configuration underlying Eq. (16) is such that two correlated particles are very close, whereas the third one is far from their c.m. Therefore in Eq. (18), which, we reiterate, is expected to correctly describe the spectral function only for high values of k and E, the relevant contribution has to be provided by the low-momentum part of $n_{\rm c.m.}$ and by the high-momentum part of $n_{\rm rel}$. Such a configuration is automatically generated by the use of the c.m. momentum distribution in the $l=0$ state, which, for $k>1.5\ {\rm fm}^{-1}$, does not include the high-momentum components generated by the short-range and tensor correlations. An inspection of Eq. (18) shows qualitatively some relevant features of the spectral function: (i) if $n_{\rm rel}$ and $n_{\rm c.m.}$ are described within an independent particle model (e.g., Gaussians with the same length parameter), Eq. (18) predicts a maximum of the spectral function close to

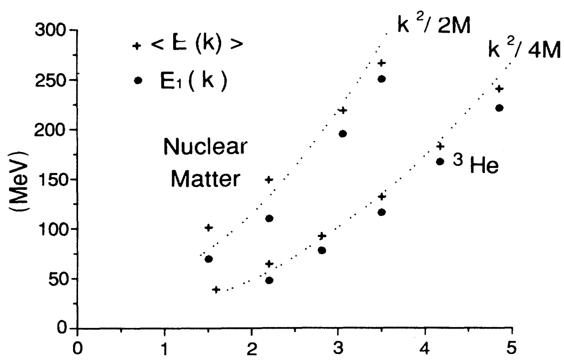

FIG. 1. Comparison of the values of the mean removal energy $\langle E(k)\rangle$ (crosses) and the peak position $E_1(k)$ (solid circles) for ^{3}He and nuclear matter, calculated with the spectral functions of Refs. 4 and 6, respectively, with the prediction (double-dotted lines) of the 2NC model given by Eqs. (14) and (15) [i.e., $\langle E(k)\rangle=E_1(k)=E_{\rm thr}+k^2/4M$ for ^{3}He and $\langle E(k)\rangle=E_1(k)=E_{\rm thr}+k^2/2M$ for nuclear matter].

$E=E_{\rm thr}$ with a monotonic decrease with E; (ii) if one makes the very reasonable assumption that the low-momentum part of $n_{\rm c.m.}$ could be described by a Gaussian distribution, Eq. (18) predicts that, because of the k_3 and k_0 dependence of $n_{\rm rel}$, the spectral function will exhibit peak-shaped behavior with the peak position located at a value lower than the one predicted by the 2NC model (i.e., $E=E_{\rm thr}+k^2/4M$); (iii) the shift of the peak position with respect to the 2NC model, as well as the shape of the spectral function in the vicinity of the peak, are mostly governed by the high k_0 dependence of $n_{\rm rel}$. If also the latter is chosen in the Gaussian form, the peak position is located at a value of E given by

$$E_1(k)\cong E_{\rm thr}+\frac{k^2}{4M}\left[1-2\frac{\langle k^2_{\rm c.m.}\rangle}{\langle k^2_{\rm rel}\rangle}\right], \tag{19}$$

where $\langle k^2_{\rm rel}\rangle$ and $\langle k^2_{\rm c.m.}\rangle$ are the mean-square momenta associated to the high- and the low-momentum parts of $n_{\rm rel}$ and $n_{\rm c.m.}$, respectively. The full width at half maximum (FWHM) $\Gamma(k)$ is

$$\Gamma(k)\cong ak\langle k^2_{\rm c.m.}\rangle^{1/2}\left[1-\frac{\langle k^2_{\rm c.m.}\rangle}{\langle k^2_{\rm rel}\rangle}\right], \tag{20}$$

where $a=(8\ln 2/3)^{1/2}/M=0.285$ fm.

Let us comment on the above results. Equations (19) and (20), which are valid provided $\gamma\equiv\langle k^2_{\rm c.m.}\rangle/\langle k^2_{\rm rel}\rangle\ll 1$, can be shown to be the first terms of a series expansion in terms of the parameter γ, independently of the shape of $n_{\rm rel}$ and $n_{\rm c.m.}$.[10] These equations show again that in the limit of a static spectator nucleon (i.e., $\langle k^2_{\rm c.m.}\rangle\to 0$) the 2NC model is recovered [i.e., $E_1(k)=E_{\rm thr}+k^2/4M$ and $\Gamma(k)=0$]. The motion of the spectator nucleon, coupled, through energy and momentum conservation, to the motion of the pair [cf. Eq. (18)], produces both a shift (by a percentage amount of order $\cong 2\gamma$) of the peak position from the value predicted by the 2NC model, as well as the removal energy dependence of the spectral function for $E\neq E_1(k)$. It can be seen, in particular, that the link between k, k_3, and k_0 which is present in $n_{\rm rel}$, decreases the width produced by a Gaussian distribution for $n_{\rm c.m.}$ by a percentage of the order $\cong\gamma$. Using the values $\langle k^2_{\rm rel}\rangle\cong 5.8$

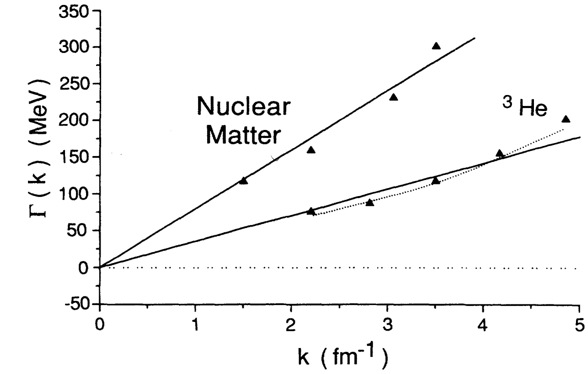

FIG. 3. The full width at half maximum $\Gamma(k)$ of the spectral function of ^{3}He and nuclear matter corresponding to the spectral functions of Refs. 4 and 6, respectively (solid triangles), compared with the predictions of Eq. (18) evaluated with Gaussian distributions (solid lines); for ^{3}He the dotted line represents the results of the calculations obtained using [in Eq. (18)] realistic momentum distributions from Refs. 4 and 5. The double-dotted line represents the prediction by the 2NC model.

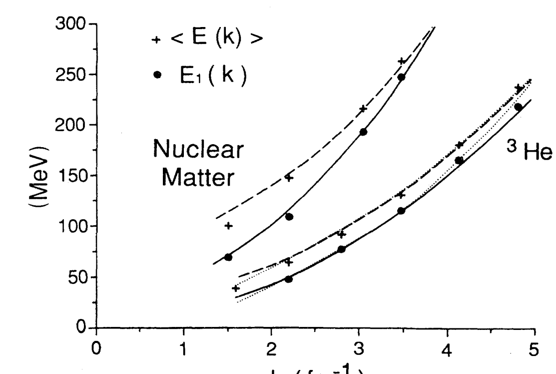

FIG. 2. Comparison of the mean removal energy $\langle E(k)\rangle$ (crosses) and the peak position $E_1(k)$ (solid circles) calculated with the spectral function of Ref. 4 for ^{3}He and the spectral function of Ref. 6 for nuclear matter, with the predictions of our model spectral function [Eq. (18)]. The solid lines and dashed lines represent $E_1(k)$ and $\langle E(k)\rangle$, respectively, calculated using Gaussian distributions in Eq. (18); for ^{3}He, the dotted lines represent the results obtained when in Eq. (18) the Gaussian distributions are replaced by realistic momentum distributions from Refs. 4 and 5.

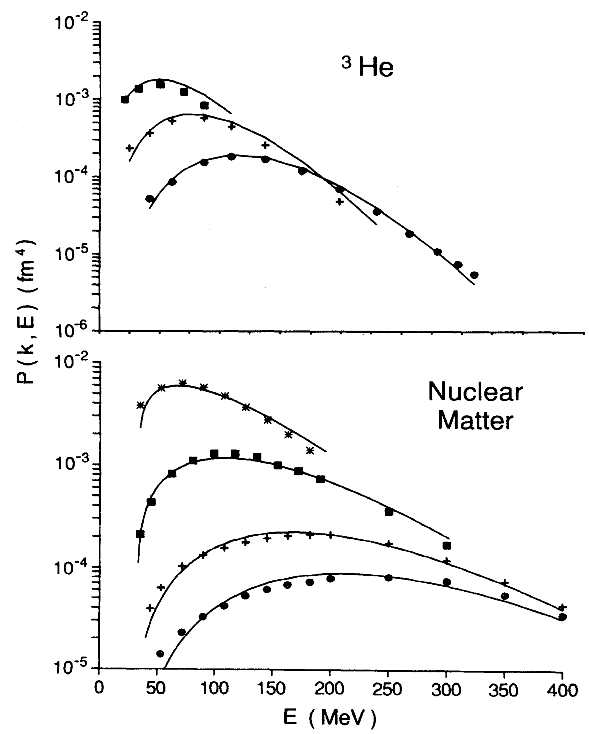

FIG. 4. The spectral function of ^{3}He (Ref. 4) and nuclear matter (Ref. 6) vs the removal energy E for various values of the nucleon momentum: $k=1.5$ fm^{-1} (asterisks), $k=2.2$ fm^{-1} (solid squares), $k=3$ fm^{-1} (crosses), and $k=3.5$ fm^{-1} (solid circles). The solid lines represent the predictions of Eq. (18).

fm^{-2} and $\langle k^2_{\mathrm{c.m.}}\rangle \cong 0.5\ \mathrm{fm}^{-2}$ resulting from many-body calculations,[4,5] one obtains that in ^{3}He $\gamma \cong 10\%$. After a proper generalization of Eq. (18) to complex nuclei, the prediction of our model for ^{3}He and nuclear matter are compared in Figs. 2–4 with the results of many-body calculations. For ^{3}He, both the Gaussian and realistic momentum distributions have been used; for nuclear matter, $n_{\mathrm{c.m.}}$ has been obtained from a Fermi-gas momentum distribution properly rescaled to account for *NN* correlation depletion, whereas for n_{rel} a Gaussian form with $\langle k^2_{\mathrm{rel}}\rangle \cong 7.5\ \mathrm{fm}^{-2}$ compatible with many-body calculations has been adopted (the details of calculations will be presented elsewhere[10]). The results presented in Figs. 2–4 deserve the following comments:

(i) Unlike the 2NC model in which $\langle E(k)\rangle = E_1(k)$, in disagreement with the results of theoretical calculations, Eq. (18) is able to correctly predict the relation $\langle E(k)\rangle > E_1(k)$ (cf. Fig. 2).

(ii) The values of the FWHM $\Gamma(k)$, which is obviously zero in the 2NC model, is correctly predicted by Eq. (18). Really, the approximation of ignoring the c.m. motion of the correlated pair is equivalent to neglecting the term linear in k in the quantity $\langle E(k)\rangle$; such a linear term is responsible for the linear dependence of Γ on k. It turns out that from the results presented in Fig. 3, the linear dependence of Γ upon k [Eq. (20)] provides a satisfactory reproduction of the average value of $\Gamma(k)$ up to large values of k; at the same time, it also appears that the calculations with the spectral function also give rise to terms quadratic in k, which seem to be reproduced by Eq. (18) evaluated with realistic momentum distributions.

(iii) It appears that not only the values of $\Gamma(k)$, $\langle E(k)\rangle$, and $E_1(k)$ are correctly predicted by Eq. (18), but also as can be seen from Fig. 4, the whole shape of $P_1(k,E)$ is satisfactorily reproduced in a wide range of values of E around the peak.

(iv) The values of $n(k)$ [Eq. (7)], $\langle T\rangle$ [Eq. (8)], and $\langle E\rangle$ [Eq. (9)] calculated using Eq. (18), are in very good agreement with the corresponding quantities calculated with the spectral functions of Refs. 4 and 6.

The results presented in this paper show that the basic mechanism which qualitatively produces the peaks of the spectral function is the two-nucleon correlation configuration.[1] At the same time, Eq. (18) represents a remarkable improvement of the original naive 2NC model; as a matter of fact, by taking into account the motion of the c.m. of the correlated pair and its coupling to k and E through energy and momentum conservation, not only the peak position $E_1(k)$ and the mean removal energy $\langle E(k)\rangle$ are quantitatively predicted, but, more importantly, the absolute value of the spectral function and its k and E dependences for $E \neq E_{\mathrm{thr}} + (A-2)k^2/2(A-1)M$, are generated. Equation (18) appears, therefore, to be suitable for the description of the nucleon spectral function at large values of k and E. The next improvement to be considered concerns the contributions from three-nucleon correlations, which would affect the predictions of Eq. (18) for values of E much lower and much higher than the peak position. In closing this paper, we would like to point out that in a previous work of ours[11] a model spectral function was proposed in which the energy dependence was assumed *ab initio,* rather than obtained, as in the present paper, from some dynamical underlying *NN* correlation mechanism; the results presented here allow one to understand the microscopic validity of the model of Ref. 11, at least for values of E not very far from the peak.

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