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# Quasiparticle Pole Strength in Nuclear Matter*

R. S. Poggioli
*Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742*

and

A. D. Jackson
*Department of Physics, State University of New York, Stony Brook, New York 11790*
(Received 18 August 1975)

It is argued that single-particle-like behavior in nuclear matter is much less probable than Brueckner theory suggests. In particular, the quasiparticle pole strength is evaluated for nuclear matter and it is shown that, contrary to the spirit of Brueckner theory, low-momentum states play a crucial role in determining the magnitude of $z_{k_F}$.

In Brueckner theory, the probability that nuclear matter cannot be described adequately in terms of single-particle-like behavior is given by $\kappa$, Brandow's defect-wave-function probability.[1] Earlier calculations have estimated $\kappa \approx 0.20$. The smallness of $\kappa$ is usually offered as an explanation for the success of the independent-particle (shell) model of nuclei. Unfortunately, all previous calculations of $\kappa$ have assumed that high-momentum states alone provide the dominant contribution. While this is certainly true for the ground-state energy, the authors have shown in an earlier paper[2] that many other properties of nuclear matter are strongly affected by contributions from low-lying states. In the present paper, it will be shown that these low-lying states have a pronounced effect on single-particle-like behavior, making it much less probable.

Let us begin with a brief review of the pertinent concepts of Brueckner theory: Since the internucleon force is short ranged, two-body scattering dominates. Since the nuclear force is strong, high-momentum particle states dominate because of their clear phase-space advantage (over hole states, in particular). The appropriate, correlated two-body wave function is

$$\Psi = \Phi - (Q/e)V\Psi \tag{1}$$

in which $\Phi$ is the uncorrelated wave function and the Pauli operator $Q$ excludes hole states. This equation becomes identical to the free scattering equation if the Pauli operator is replaced by unity. In this case, the zero in the energy denominator, corresponding to energy conservation, leads to the outgoing scattered wave. In Eq. (1), however, the Pauli operator prevents the energy denominator from vanishing. Hence, there can be no real (energy conserving) scattering and, at sufficiently large distances, the correlated wave function must approach the uncorrelated wave function or, equivalently, the defect wave function

$$\zeta = \Phi - \Psi$$

must vanish. This is the chief effect which the presence of the other particles (the Fermi sea) has on the two scattering particles. In nuclear matter, $\Psi$ approaches the uncorrelated plane wave very rapidly; this phenomenon is called "healing."[3] At extremely small distances, the core region of the internucleon potential makes $\Psi$ negligibly small, thus producing a "wound" in the wave function; however, this wound heals very rapidly. In other words, $|\zeta(\vec{r})|$ is approximately unity in the core region where the particles are strongly correlated and goes rapidly to zero as $r$ increases. It is useful to define the range $d$ of the two-body correlations by

$$\tfrac{4}{3}\pi d^3 = \int |\zeta(\vec{r})|^2 d^3r. \tag{2}$$

This distance should be compared with the average interparticle spacing $r_0$ defined by

$$\tfrac{4}{3}\pi r_0^{\,3} = n^{-1} \tag{3}$$

in which $n$ is the density of the system. For nuclear matter, $d$ is considerably less than $r_0$. Since within a sphere of radius $r_0$ centered on any particle there is, on the average, one other particle, the probability of strong two-body correlations is $(d/r_0)^3$. Equivalently, this is the probability that a particle cannot be described adequately in terms of single-particle-like behavior. Similarly, the probability that three particles will be sufficiently close together to be strongly correlated is $(d/r_0)^6$ and so on for higher-order correlations. Hence, the "small parameter" of Brueckner theory is $\kappa$, Brandow's defect-wave-function probability:

$$\kappa = (d/r_0)^3. \tag{4}$$

[In defining $\kappa$, Brandow took into account the effect of exchanges; his definition therefore differs slightly from Eq. (4).]

Actually, independent-particle-like behavior is much more common than these arguments, based on Brueckner theory, would suggest. For example, liquid $He^3$ and conduction electrons in a solid exhibit a similar behavior. In fact, with any normal Fermi liquid one can associate a reference gas of "quasiparticles" in order to describe the low-lying excitation spectrum.[4] Microscopically, this is just a manifestation of the existence of poles in the one-particle Green's function. In the vicinity of this quasiparticle pole, the Green's function behaves as

$$G(\vec{k},\omega) \approx \frac{z_{\vec{k}}}{\epsilon(\vec{k})/\hbar - \omega} \tag{5}$$

which, of course, is similar to the Green's function of an ideal gas. In general, therefore, the strength of single-particle-like behavior is given by the residue at the quasiparticle pole,

$$z_{\vec{k}} = \left(1 - \hbar^{-1} \frac{\partial \Sigma(\vec{k},\omega)}{\partial \omega}\bigg|_{\omega = \epsilon(\vec{k})/\hbar}\right)^{-1}. \tag{6}$$

An expansion for the self-energy is developed in PJ1. A model space is introduced in order to take special care of the contributions from low-lying states. The high-momentum states excluded from the model space are incorporated into the model interaction. As suggested by Brueckner theory, a truncated $G$-matrix approximation is used for this model interaction. To first order in the model interaction $G_M(\omega)$, the self-energy is given by

$$\Sigma_1(\vec{k},\omega) = \frac{i}{2\pi} \sum_{q<k_M} \int_C d\nu \, [\langle \vec{k},\vec{q}|G_M(\omega+\nu)|\vec{k},\vec{q}\rangle - \langle \vec{k},\vec{q}|G_M(\omega+\nu)|\vec{q},\vec{k}\rangle] \, G(\vec{q},\nu), \tag{7}$$

where $C$ is the contour formed by the real $\nu$ axis and a semicircle at infinity in the upper half of the complex $\nu$ plane. In PJ1, it is argued that the model interactions, describing excitations to intermediate states of high relative momentum by the short-ranged core region of the internucleon force, are essentially instantaneous. A dimensionless parameter $\kappa_M$ is introduced in order to describe this property quantitatively:

$$\kappa_M = -\hbar^{-1} \sum_{q<k_F} \frac{\partial \langle \vec{k},\vec{q}|G_M(\omega)|\vec{k},\vec{q}\rangle}{\partial \omega}\bigg|_{k=k_F;\, \omega = 2\mu/\hbar}. \tag{8}$$

As discussed in PJ1, $\kappa_M$ is only 0.10 for nuclear matter. To the extent that effects of the order $\kappa_M$ can be neglected (as assumed in PJ1), the first-order approximation for the self-energy [Eq. (7)] is independent of $\omega$ and, consequently, does not contribute to the quasiparticle pole strength. On the other hand, $\partial\Sigma_1/\partial\omega$, by definition, would actually represent the only renormalization of the quasiparticle pole strength if the high-lying states alone determined the properties of the system (since, in all higher orders of the perturbative expansion, low-lying states contribute). Therefore, a straightforward extension of Brueckner theory suggests that this term will dominate. In fact, $\kappa_M$ is just equal to that part of Brandow's $\kappa$ [Eq. (4)] which is associated solely with the high-momentum states.[1] In order to see which assertion is correct, it is necessary to evaluate higher-order terms in the perturbative expansion. The total second-order contribution to the self-energy is given by

$$\Sigma_2(\vec{k},\omega) = -\frac{1}{2\hbar}\left(\frac{1}{2\pi}\right)^2 \sum_{q_i<k_M} \int_{-\infty}^{+\infty} d\nu_1 \int_{-\infty}^{+\infty} d\nu_2 \int_{-\infty}^{+\infty} d\nu_3 \, |\langle \vec{k},\vec{q}_1|G_M(\omega+\nu_1)|\vec{q}_2,\vec{q}_3\rangle - \langle \vec{k},\vec{q}_1|G_M(\omega+\nu_1)|\vec{q}_3,\vec{q}_2\rangle|^2$$
$$\times G(\vec{q}_1,\nu_1) G(\vec{q}_2,\nu_2) G(\vec{q}_3,\nu_3) \delta_{\vec{k}+\vec{q}_1,\, \vec{q}_2+\vec{q}_3} \delta(\omega+\nu_1-\nu_2-\nu_3). \tag{9}$$

Even if the $\omega$ dependence of the model interaction is neglected, one obtains

$$-\hbar^{-1}\frac{\partial\Sigma_2(\vec{k},\omega)}{\partial\omega}\bigg|_{k=k_F;\,\omega=\mu/\hbar}\approx 0.36$$

when only the $S$-wave components of $G_M$ are retained; the addition of $P$ waves produces an even larger value, 0.40. It is clear that the low-lying states play an essential role in determining the magnitude of the quasiparticle pole strength. Furthermore, it is reasonable to neglect effects of the order $\kappa_M$. The standard Brueckner approximation for $z_{k_F}$, namely $1-\kappa$, is clearly inadequate because it ignores the crucial effect of the low-momentum states. Brueckner theory does not take into account the possibility of special long-ranged correlations produced by the (weak) tail region of the nuclear force. Unfortunately, the apparent weakness of single-particle-like behavior in nuclear matter has a most undesirable side effect: It is possible that no microscopic expansion for the properties of nuclear matter will converge sufficiently rapidly. Since $1-z_{k_F}$ represents the fraction of the time during which the single-particle Green's function is incoherent, there is no adequate approximation for this part. In fact, nuclear matter may be no more amenable to a microscopic calculation than liquid $He^3$.

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# Are There Fission-Fragment Energy Variations in $^{235}$U Neutron Resonances?

H. Weigmann and J. A. Wartena
*Central Bureau for Nuclear Measurements, EURATOM, B-2440 Geel, Belgium*

and

C. Wagemans*
*Studiecentrum voor Kernenergie—Centre d'Etude de l'Energie Nucléaire, B-2400 Mol, Belgium*
(Received 19 May 1975)

Measurements have been made to check recent findings of fission-fragment energy variations in low-energy neutron resonances of $^{235}$U. The result has been negative.

In a recent paper, Felvinci, Melkonian, and Havens[1] describe the observation of apparent variations, as a function of neutron energy, of the energy distribution of fission fragments for the neutron-induced fission of $^{235}$U. In the present Letter, we report on a very similar measurement performed at the Central Bureau for Nuclear Measurements (CBNM), Geel, Belgium, which, however, showed a negative result.

The U target assembly of the CBNM 60-MeV electron linac, including 4-cm-thick polyethylene moderator slabs, served as a pulsed neutron source. The $^{235}$U sample was exposed to the collimated neutron beam at a flight path of 8.1 m. The sample consisted of 80 $\mu$g/cm$^2$ $UF_4$ evaporated on a backing of 50 $\mu$g/cm$^2$ Vyns plus 20 $\mu$g/cm$^2$ Au. Fission fragments emerging from the sample were detected by two 2000-mm$^2$ Ortec surface-barrier detectors with a depletion depth of 100 $\mu$m. Detector signals were analyzed by a time coder operated with 1024 channels (channel width 640 nsec) and an analog-to-digital converter (64 channels), and the output of the coders was stored on magnetic tape event by event. With 640-nsec channel width, the timing resolution was, in the entire energy range covered, smaller than