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Implication of recent (p,n) spin experiments and the necessity of relativity in nuclear physics

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The recent (p,n) spin experiments on various nuclear targets at forward angles suggest that the Gamow-Teller strength is almost exhausted by nucleon excitations, which limit the Landau-Migdal parameter for the delta nucleon to $g'_\Delta \leqslant 0.2$. This small g'_Δ makes the nucleus in or very close to the condition for pion condensation and produces, if close, the precritical phenomena, which have been proved to be not occurring in the nucleus. One solution for reducing the pionic correlation is to take the relativistic description of the nuclear many-body system, which reduces the nonrelativistic pionic Lindhard function by about a factor of 2. This relativistic Lindhard function is also consistent with no enhancement of the longitudinal spin-response function against the transverse one as seen as $R_L/R_T \leqslant 1$ extracted in (p,p') and (p,n) experiments at large angles. These observations, when combined, indicate that the relativistic description is necessary to understand the low-energy properties of nucleus. [S0556-2813(99)01902-0]

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The recent (p,n) spin experiments on various nuclear targets at forward angles performed at RCNP in Osaka University have attracted strong theoretical interest [1]. The multipole decomposition of angular distributions up to high excitation energy provides the Gamow-Teller (GT) strength $S_{\beta-}$ close to the sum-rule value, $3(N-Z)$, with N and Z being the neutron and proton numbers of the target nucleus [2]. With a small $S_{\beta+}$ strength as observed to be small up to ~ 10 MeV in (n,p) reactions on ^{90}Zr [3], which should be extended to high excitation energies as in the (p,n) case, this fact suggests that the Landau-Migdal parameter for delta-nucleon coupling is small; $g'_\Delta \leqslant 0.2$ [1,4]. This upper bound can be extracted from the relation that the GT operators, $O(\beta_\pm)$, are reduced by the delta-nucleon coupling [5],

$$\tilde{O}(\beta_\pm) = O(\beta_\pm)/[1 + g'_\Delta U_\Delta]. \tag{1}$$

Here, U_Δ is the delta-hole polarization function and $U_\Delta = (8/9)(f_\pi^{*2}/m_\pi^2)(\rho/\omega_\Delta) \sim 0.8$ at the normal matter density [6]. To quantify, if S_β is $(90\pm 5)\%$ of the Ikeda sum-rule value [1], then $g'_\Delta \leqslant 0.1$ at the normal matter density, even if we use the delta-hole polarization function at half the normal matter density as an effect of finite nuclear size, $g'_\Delta \leqslant 0.2$ [5,6]. This value of g'_Δ is much smaller than the estimate of g'_Δ by using the G matrix and the induced interactions [7,8].

This interpretation causes a contradicting consequence on pion condensation or its precritical phenomena, which are expected at large momenta in the pion channel. The small g'_Δ makes the attractive contribution of the delta-nucleon correlations very large and increases the pionic collectivity at high momenta. This role of g'_Δ can be seen in the dimesic function due to a delta isobar at finite momenta [9],

$$\varepsilon_\Delta = 1 + \left(g'_\Delta - \frac{q^2}{m_\pi^2 + q^2} \right) U_\Delta . \tag{2}$$

When the repulsion g'_Δ is reduced, the attractive contribution due to the pion exchange, $q^2/(m_\pi^2+q^2)$, dominates the delta dimesic function, which enhances the pionic collectivity. In fact, the study of g'_Δ on pion condensation and its precritical phenomenon by Shiino *et al.* [10] shows that under the values $g' = g'_{\Delta\Delta} = 0.6$ the pion condensation takes place below $g'_\Delta \leqslant 0.26$ at the normal matter density. The present value, $g'_\Delta \leqslant 0.2$, is definitely inconsistent with the experimental observations of no pion condensation in a finite nucleus [11,6].

Since there is a further ambiguity in the Landau-Migdal parameter $g'_{\Delta\Delta}$ for delta-delta correlations and also the nucleon effective mass, the condition for pion condensation may not be fulfilled [12]. The estimate of g', g'_Δ, $g'_{\Delta\Delta}$ considering the relativistic effect and the induced interaction were performed by Krewald *et al.* [13]. Even in this case, if the value for g'_Δ is as small as indicated by the (p,n) experiments, the nucleus should be very close to the critical condition and hence the precritical phenomenon has to take place [9]. The enhancement of the differential inelastic cross sections leading to unnatural parity states at high momenta should be largely enhanced as the cross sections are modified as $\tilde{\sigma} = \sigma/\varepsilon^2$, where the entire dimesic function due to the pionic correlations, including the nucleon particle-hole excitations, becomes close to zero. However, such a precritical enhancement has not been observed in various experiments performed around 1980 using (p,p') reactions to unnatural parity states [6].

Hence, the recent (p,n) experiments suggest a small g'_Δ, while the missing pion condensation and its precritical phenomenon indicate a large g'_Δ. What should be the solution? Recently, there have been many activities to describe nuclei in terms of relativistic many-body theories. The relativistic Bruckner-Hartree-Fock (RBHF) theory is able to provide the saturation property of nuclear matter, which is very close to the semi-empirical value [14]. The direct use of the results of RBHF within the local-density approximation reproduces the properties of finite nuclei without any additional parameters [15]. Furthermore, the relativistic Brueckner-Hartree-Fock formalism was applied directly to finite nuclei by Fritz *et al.* with good agreement with experiments [16]. Its phenomenological version, the relativistic mean field theory, was used on many nuclei including unstable nuclei with great success [17].

The key point of the success of the relativistic description of nuclei is the presence of large scalar and vector potentials as expressed in the following Dirac equation [14]:

$$[-i\vec{\alpha}\cdot\vec{\nabla}+m\beta+U_S(r)\beta+U_V(r)]\psi=E\psi. \tag{3}$$

Here the potentials at the origin are about

$$U_S(r=0)\sim-356\ \text{MeV},$$

$$U_V(r=0)\sim275\ \text{MeV}.$$

These strong scalar and vector potentials give the large spin-orbit splittings necessary for producing the magic numbers. Hence, the effective mass comes out to be

$$m^*=m+U_s(r=0)\sim583\ \text{MeV}. \tag{4}$$

The relativistic description of nuclei provides an additional interesting consequence in the pion channel. The relativistic pion Lindhard function Π^{rel} is written as [18]

$$\Pi^{\text{rel}}=\left(\frac{m^*}{m}\right)^2\Pi, \tag{5}$$

when the widely accepted pseudovector pion nucleon coupling is adopted. Hence, the lowest pion self-energy is reduced by about 50% from the nonrelativistic value. With the use of Π^{rel}, the collectivity necessary for pion condensation and its precritical phenomenon is largely reduced. In fact, the relativistic description of pion condensation (without isobars) provides no pion condensation even without the Landau-Migdal short-range correlations, $g'=0$ [18].

If we use the relativistic description, another puzzle about the spin-response functions may also be solved. The spin experiments performed at Los Alamos and the recent RCNP experiments using (p,n) reactions provide $R_L/R_T\leqslant1$ [19–21]. This ratio, R_L/R_T, with R_L and R_T being the spin longitudinal and transverse response functions, respectively, is expected to be larger than 1 in the nonrelativistic framework. This is because the interaction in the pion channel is [6]

$$V_\pi=\frac{f_\pi^2}{m_\pi^2}\left(g'-\frac{q^2}{m_\pi^2+q^2-\omega^2}\right)\vec{\sigma}_1\cdot\hat{q}\vec{\sigma}_2\cdot\hat{q}\vec{\tau}_1\cdot\vec{\tau}_2, \tag{6}$$

while

$$V_\rho=\frac{f_\pi^2}{m_\pi^2}\left(g'-C_\rho\frac{q^2}{m_\rho^2+q^2-\omega^2}\right)\vec{\sigma}_1\times\hat{q}\cdot\vec{\sigma}_2\times\hat{q}\vec{\tau}_1\cdot\vec{\tau}_2, \tag{7}$$

in the rho meson channel, where $C_\rho\sim2$. At large momenta, $q\sim1.7\ \text{fm}^{-1}$, where the experiments are performed, V_π is negative (attractive), and V_ρ is positive (repulsive) for $g'\sim0.6$. Hence, the pion (longitudinal) response is enhanced and the rho meson (transverse) response is quenched. This fact provides $R_L/R_T\geqslant1$. However, the relativistic Lindhard function in the pion channel is reduced by about 50% as compared to the nonrelativistic one and the expected enhancement in the pion channel is not large enough to overcome this large reduction. The rho meson response is not reduced so much as the pionic case and the ratio could be less than 1 in the relativistic case [22].

In summary, we have discussed the implication of the recent (p,n) spin experiments performed at RCNP in Osaka University [1]. The RCNP data are used to deduce the Landau-Migdal parameter for the delta-nucleon as $g'_\Delta\leqslant0.2$. Under the nonrelativistic framework, this small g'_Δ causes the pionic collective phenomena in nuclei. It thus contradicts the results of high momentum transfer experiments leading to isovector unnatural parity states, which show no anomaly. We have shown then that the relativistic description of nuclei can accommodate these two seemingly contradicting experimental results [large $g'_\Delta=0.6$ from (p,p') experiments at large momentum transfer, and small $g'_\Delta\leqslant0.2$ from (p,n) experiments at small momentum transfer]. The small nucleon effective mass, $m^*\sim580$ MeV due to the deep scaler potential in the relativistic model accommodates the small g'_Δ and the nonexistence of the collective pionic effects in the nuclei. It has been also shown that the small effective nucleon mass explains the observed abnormal behavior of the ratio of the spin longitudinal to transverse responses, R_L/R_T, that is less than one.

In this paper, we have made rough estimates of various quantities as the dimesic functions and the spin-response functions. Particularly, these quantities have been estimated in nuclear matter for the sake of easier discussion. We need to work out the details of those processes in future work. On the experimental side, we have to confirm the GT strength at higher excitation energies by performing extensive (n,p) experiments.

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