Pionic Modes Studied by Quasielastic $(\bar{p}, \bar{n})$ Reactions

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It has long been expected that the pionic modes show some collective phenomena such as the pion condensation in the high density nuclear matter and its precursor phenomena in the ordinary nuclei. Here we show an evidence of the precursor observed in the isovector spin longitudinal cross sections $I_{Dq}$ of the quasielastic $^{12}$C, $^{40}$Ca $(\bar{p}, \bar{n})$ reactions at $T_p = 346$ and 494MeV with the momentum transfer $q = 1.7\text{fm}^{-1}$. Another aim of this report is to evaluate the Landau-Migdal parameters $g_{NN}^{'}, g_{N}\Delta$ and $g_{\Delta}\Delta$ at the large momentum region from the above reactions. We obtained $g_{NN}^{' \approx 0.6 - 0.7, g_{N}\Delta \approx 0.3 - 0.4}$. The results are consistent with those at the small momentum region, which are obtained from the Gamov-Teller strength distribution.

I. INTRODUCTION

I think that everybody agrees that the pions, predicted by Yukawa in 1935, still play a crucial role in nuclear physics. They couple with the nucleon in the form of $\tau \sigma \cdot q$ where $q$ is the pion momentum. Therefore once the real or virtual pions are absorbed by the nucleus, they create the isovector spin longitudinal modes, i.e. the pionic modes.

It has long been expected that the modes show some collective phenomena. The most famous one is the pion condensation, which may appear in high density nuclear matter such as the neutron star. Its appearance must have very important effects on the equation of state and the cooling processes of the neutron star.

The condensation is considered not to realize in the normal nuclei because the critical density $\rho_c$ of the phase transition has been evaluated to be much higher than the normal density $\rho_0$. However, we may expect to see some precursor phenomena even in the normal nuclei. Among them, here, we are interested in the enhancement of the isovector spin longitudinal response function

$$R_L(q, \omega) = \sum_{n} |\langle n| \sum_{i} \tau_i^a (\sigma_i \cdot \hat{q}) e^{i q \cdot r_i} |0 \rangle|^2 \delta(\omega - (E_n - E_0))$$

around the quasielastic region, where $q$ is the momentum transfer, $\hat{q}$ is its unit vector, $\omega$ is the energy transfer and $E_n$ is the intrinsic energy of the $n$-th nuclear state (0 denoting the ground state). The superscript $a$ denotes the isospin component, $a = +, 0, -$ where $a = -$ corresponds to those obtained by the $(p, n)$ reaction. To make the notation simple, we suppress the superscript $a$ in the r.h.s. and below.

I would like to make the following two comments. The first is that the real or virtual photon couples with the nucleon in the form of $\tau \sigma \times q$ for the spin-isospin channel, and thus creates only the isovector spin transverse modes but not the spin longitudinal modes. Therefore the reliable probe $(e, e')$ is not suitable to investigate the pionic modes, but it fits to see the isovector spin transverse response function

$$R_T(q, \omega) = \frac{1}{2} \sum_{n} \sum_{\mu} |\langle n| \sum_{i} \tau_i^a (\sigma_i \times \hat{q})_\mu e^{i q \cdot r_i} |0 \rangle|^2 \delta(\omega - (E_n - E_0))$$

In this report I will not touch the spin transverse part because of lack of time.

Another point is that the momentum $q$ is not a good quantum number in the actual nuclei, because they are of finite size. Therefore the spin longitudinal and the spin transverse modes are mixed in a certain discrete state. Each mode is selected by the probe used. Here we are concerned only with the gross structure of the energy spectra around the quasielastic peak.
II. ORIGIN OF THE COLLECTIVITY –EFFECTIVE INTERACTIONS

The collectivity of the pionic modes is considered to come from (1) the attraction of OPEP and (2) the coupling with the Δ-hole states.

To evaluate the collectivity we need the effective interactions for the ph-ph, ph-Δh and Δh–Δh couplings. The ph-ph part of the spin-isospin channel is written as

\[
V(q, \omega) = (\tau_1 \cdot \tau_2)[V_L(q, \omega)(\sigma_1 \cdot \hat{q})(\sigma_2 \cdot \hat{q}) + V_T(q, \omega)(\sigma_1 \times \hat{q})(\sigma_2 \times \hat{q})]
\]  

where the \(V_L\) and \(V_T\) parts are the spin longitudinal and the spin transverse interactions, respectively. The expression is equivalent to the familiar form, the sum of the central and the tensor parts. Extension to the ph-Δh and Δh–Δh interactions are straightforward.

They are often represented by the π + ρ + \(g'\) model, which expresses the interaction as the one pion exchange plus the one \(\rho\)-meson exchange plus the contact interaction specified by the three Landau-Migdal parameters, \(g'_{NN}\), \(g'_{N\Delta}\) and \(g'_{\Delta\Delta}\). In this model \(V_L\) and \(V_T\) are expressed as

\[
V_L(q, \omega) = \frac{f^2_{\pi NN}}{m^2_\pi} \left( g' + \frac{q^2}{\omega^2 - q^2 - m^2_\pi} \Gamma^2_\pi(q, \omega) \right),
\]

\[
V_T(q, \omega) = \frac{f^2_{\pi NN}}{m^2_\pi} \left( g' + \frac{q^2}{\omega^2 - q^2 - m^2_\rho} C_\rho \Gamma^2_\rho(q, \omega) \right).
\]

where \(C_\rho\) is the coupling ratio between the π and ρ exchange and \(\Gamma_{\pi(\rho)}\) are the coupling form factor of the π(\rho)NN vertex. Their \(q\) dependence are shown in Fig. 1 for \(\omega = 80\) MeV and \(g' = 0.6\). The genuine one pion exchange part \(V_\pi (g' = 0)\) is also shown (dashed line). We see that \(g'\) represents the strength at \(q = 0\) and determines above what \(q\) the interaction \(V_L\) becomes negative and how attractive it is at large \(q\), which are crucial for the pionic collectivity. Therefore it is one of the main aims of this report to estimate the \(g'\)’s.

![FIG. 1. Effective interaction. \(C_0 = f^2_{\pi NN}/m^2_\pi\).](image)

Recently Suzuki and Sakai [4] phenomenologically estimated them from the energy of the giant Gamov-Teller (GT) resonance and the quenching factor \(Q\) for the GT sum rule value observed by Wakasa et al. [5], where \(Q\) is defined as

\[
Q = \frac{S^\text{exp}_{\beta^+} - S^\text{exp}_{\beta^-}}{3(N - Z)} \quad \text{with} \quad S^\beta_\tau = \sum_n |\langle n|\tau^\pm|0\rangle|^2.
\]

Using the Fermi gas model and the sum rule technique, they obtained

\[
0.58 < g'_{NN} < 0.59, \quad 0.18 < g'_{N\Delta} < 0.23 \quad \text{if} \quad g'_{\Delta\Delta} \leq 1.0,
\]

Arima et al. [6] reported that the finiteness increases \(g'_{N\Delta}\) by about 0.1. This is the estimation at \(q \approx 0\). Then what happens at large \(q\) ?

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III. EXPERIMENTAL METHOD TO STUDY THE PIONIC MODES

Since the reliable probe \((e, e')\) does not work for study of the spin longitudinal responses, we have inevitably to utilize the hadronic probes though their reaction mechanism is more complex. The best one could be the \((\vec{p}, \vec{n})\) reactions, for which we need the polarized proton beam with high intensity and the neutron polarimeter with high efficiency.

Due to these difficulties, complete measurement of the polarization transfer coefficients \(D_{ij}(D_{SS'}, D_{NN'}, D_{LL'}, D_{SL'}, D_{LS'})\) of the \((\vec{p}, \vec{n})\) reactions became possible just in 1990’s. The coefficient \(D_{ij}\) represents the transition probability from the proton with the spin polarization in the direction \(i\) to the neutron with the spin polarization in the direction \(j\). The directions are specified in Fig. 2.

![FIG. 2. Spin direction assignment](image)

To extract the spin response functions, Bleszynski et al. \cite{9} introduced the spin longitudinal cross section \(I_{Dq}\) and the spin transverse cross section \(I_{Dp}\), etc., which are defined by the linear combinations of \(D_{ij}\) times the unpolarized cross section \(I\). The naming comes from the fact that \(I_{Dq}(p, \omega) = K \left( N_{eff}/N \right) I_{NN}D_{NN}q R_L(q, \omega) \) (3.1) \(I_{Dp}(q, \omega) = K \left( N_{eff}/N \right) I_{NN}D_{NN}p R_T(q, \omega) \) (3.2) if the plane wave impulse approximation (PWIA) with the \(N_{eff}\) prescription works. Here \(K\) is the kinematical factor, \(N_{eff}\) is the number of neutrons which participate the reaction and \(I_{NN}D_{NN}\) is the corresponding quantity of the \(NN\) scattering.

In this report we concentrate on only the pionic modes, consequently only the spin longitudinal cross sections \(I_{Dq}\).

IV. THEORETICAL APPROACH TO THE SPIN LONGITUDINAL RESPONSE

We must fully take into account the finite size feature of the nucleus, since it mixes up the spin longitudinal and the spin transverse modes. On top of that we are interested in the gross collective nature in the continuum. Therefore we employed the continuum random phase approximation (RPA) method in the angular momentum representation.

In preparation of the single particle states and the single particle Green’s functions, we use a radial dependent effective mass \(m^*(r)\), and treat the spreading widths of the holes and the particles by the complex binding energy and the complex potential, respectively. The \(\Delta\)-hole configurations are included in the continuum RPA formalism and the \(\pi + \rho + g'\) model interaction is utilized. Most of previous analyses were carried out in the approximation \(g'_{NN} = g'_{N\Delta} = g'_{\Delta\Delta}\), which is called the universality ansatz. We remove this ansatz and treat these \(g'\)’s independently.

In hadronic reactions the distortion and absorption must be taken into account. Therefore we developed a formalism of the distorted wave impulse approximation (DWIA) for the continuum final states incorporating with the continuum RPA.

V. NUMERICAL ANALYSIS OF \(^{12}\text{C}, ^{40}\text{Ca} (\vec{p}, \vec{n})\) REACTIONS

Using the above DWIA + continuum RPA method, we analyzed the \(^{12}\text{C}, ^{40}\text{Ca}(\vec{p}, \vec{n})\) reactions at \(T_p = 346\text{MeV}\) and \(\theta = 22^\circ\) by Wakasa et al. \cite{8,12} and at \(T_p = 494\text{MeV}\) and \(\theta = 18^\circ\) by Taddeucci et al. \cite{7} In the both cases the transferred momentum \(q\) is about \(1.7\text{fm}^{-1}\) for \(\omega < 120\text{MeV}\).
FIG. 3. The spin longitudinal cross section $ID_\phi$ of $^{12}$C, $^{40}$Ca($\vec{p},\vec{n}$) at $T_p = 346$MeV and $\theta = 22^\circ$. In RPA $(g^\prime_{NN}:g^\prime_{N\Delta}:g^\prime_{\Delta\Delta}) = (0.7, 0.3, 0.5)$ and $m^*(0) = 0.7m$ are used.

We treated the Landau-Migdal parameters $g^\prime_{NN}$, $g^\prime_{N\Delta}$ and the effective mass at the nuclear center $m^*(r = 0)$ as adjustable parameters. The calculated spin longitudinal cross sections $ID_\phi$'s with and without the RPA correlations are compared to the experimental results in Fig. 3 for the $T_p = 346$MeV cases and Fig. 4 for the $T_p = 494$MeV cases. As for the experimental results of the $T_p = 346$MeV cases, we quoted the latest results [12] instead of the published ones.
FIG. 4. $ID_q$ of $^{12}\text{C},^{40}\text{Ca}(\vec{p},\vec{n})$ at $T_p = 494\text{MeV}$ and $\theta = 18^\circ$. In RPA, $(g'_{NN},g'_{N\Delta},g'_{\Delta\Delta}) = (0.6,0.3,0.5)$ and $m^*(0) = 0.7m$ are used.

We could reproduce $ID_q$ reasonably well if we include the RPA correlation with the parameters $g'_{NN} = 0.6 - 0.7$, $g'_{N\Delta} = 0.3 - 0.4$ and $m^*(0) = 0.7m$. We fixed $g'_{\Delta\Delta} = 0.5$ but its dependence is very weak. Comparing to the results without the correlation (denoted by "free" in the figures), we clearly see the enhancement of the spin longitudinal cross sections. Thus we first found the precursor phenomena of the pion condensation.

VI. CONCLUSION

We analyzed the quasielastic $(\vec{p},\vec{n})$ reactions by the DWIA + continuum RPA method. Adjusting $g'_{NN}$, $g'_{N\Delta}$ and $m^*(0)$, we could reproduce the observed spin longitudinal cross section $ID_q$.

The analysis shows in the first time an experimental evidence of the precursor phenomena of the pion condensation, i.e. the enhancement of the spin longitudinal response function $R_L$.

Our estimation of $g'$s at $q = 1.7\text{fm}^{-1}$ from $ID_q$ gives $g'_{NN} = 0.6 - 0.7$, $g'_{N\Delta} = 0.3 - 0.4$, which are close to those at $q \approx 0$ estimated from the GT strength distribution. This means that the $\pi + \rho + g'$ model with constant $g'$s works well for wide range of $q$.

Our findings imply that the various old calculations of the critical density $\rho_c$ of the pion condensation based on the universality ansatz should be redone. It may give a great modification on the equation of state and the scenario of the cooling of the neutron star.

I did not touch the spin transverse response functions due to shortage of the time, but I must mention at the end that the observed $R_T$'s by $(p,n)$ are much larger than those obtained by $(e,e')$ and this contradiction must be solved before reaching the definite conclusion.
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