Glauber isovector spin responses for \((\vec{p},\vec{n})\) reactions at 494 MeV

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Abstract

The separated isovector spin-longitudinal and spin-transverse responses from a recent \((\vec{p},\vec{n})\) quasi-free experiment at 494 MeV are analyzed in a Glauber theory framework up to two-step contributions. Nuclear correlations are treated in the continuum random phase approximation, accounting for the spreading width of the particle-hole states. A good description of the spin-longitudinal response is achieved, hinting at some evidence of pionic effects in the quasi-elastic region. The spin-transverse response is underestimated and we show that multistep contributions, while sizable, are not sufficient to provide an explanation of the discrepancy.

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In recent experiments [1,2,3] complete sets of polarization transfer coefficients have been measured for quasifree ($\vec{p},\vec{n}$) scattering from $^2$H, $^{12}$C and $^{40}$Ca at 494 MeV. Three scattering angles have been considered, namely 12.5°, 18° and 27°, corresponding to momentum transfers $q = 1.2, 1.7$ and 2.5 fm$^{-1}$ at the quasielastic peak (QEP).

These experiments were prompted by the prediction [4], based on the $g'+\pi+\rho$ model of the residual particle-hole (ph) interaction, that the attractive pion field should induce, at momentum transfers of the order of $1 \div 2$ fm$^{-1}$, a softening and an enhancement of the isovector spin-longitudinal ($\sigma \cdot q$) response ($R_L$), whereas a quenching and a hardening should occur in the isovector spin-transverse ($\sigma \times q$) channel ($R_T$).

The original calculation, based on the random phase approximation (RPA) in a simple infinite nuclear matter model, predicted a large $R_L/R_T$ ratio. However, a first ($\vec{p},\vec{p}'$) experiment, performed at $q = 1.7$ fm$^{-1}$ [5,6], found a ratio consistent with, and even below, one. Of course, ($\vec{p},\vec{p}'$) reactions do not allow the separation of the isospin components in the response functions. As a consequence, the interpretation of the above result was actually rather uncertain and model dependent.

Charge-exchange reactions are not affected by this shortcoming and were expected to allow, in principle, a reliable mapping of the spin-isospin ph interaction in nuclei. Hence, more ambitious ($\vec{p},\vec{n}$) experiments at three different momentum transfers have been carried out [1,2,3], still showing, however, no evidence for pion induced effects in the ratio $R_L/R_T$, which is again around or below one. On the other hand, the absence of any isoscalar contamination allows a separation of the spin response functions on much firmer grounds, making a direct comparison to the calculated responses more reliable.

A word of caution is in order here. The extraction of the responses from the polarization observables is, strictly speaking, model dependent, since it relies on phenomenological $NN$ amplitudes and on a specific model for the treatment of distortion and absorption (for details on the extraction procedure see Ref. [2]). While the first issue is not a severe one, because the phenomenological $NN$ amplitudes give in fact a fairly good description of the $^2$H data, the treatment of the reaction mechanism is more delicate, since in Ref. [2] a simple effective number approximation has been employed in performing the separation, defining the polarization observables as combinations of response functions times the effective number of participating nucleons,

$$N_{\text{eff}} = \int dB \, T(b) e^{-\bar{\sigma}_{\text{tot}} T(b)},$$

with

$$T(b) = \int_{-\infty}^{+\infty} dz \, \rho(r = \sqrt{b^2 + z^2}),$$

$\rho(r)$ being the nuclear density and $\bar{\sigma}_{\text{tot}}$ the effective $NN$ total cross section. The latter is given by [7],

$$\bar{\sigma}_{\text{tot}}(E) = \frac{2m}{k} J_W/A,$$

where the parametrization $J_W/A = 0.6E$ MeV fm$^3$ is adopted and $m$, $k$ and $E$ are mass, momentum and kinetic energy of the projectile (actually, an average over the incoming
proton and outgoing neutron energies is taken); \( \tilde{\sigma}_{\text{tot}} \) turns out to be \( \approx 26 \text{ mb} \) and the effective number of neutrons \( \approx 2.3 \) in \(^{12}\text{C}\). It should, however, be understood that this simply amounts to a definition of the experimental response functions “per nucleon”: the latter, in principle, may contain contributions going beyond the effective number treatment (those due to more sophisticated reaction mechanisms) and, accordingly, the comparison to response functions extracted from electromagnetic reactions might be questionable; yet, these hadronic responses represent a legitimate experimental observable.

In Ref. [3] the experimental response functions have been compared to calculations in a model based on the distorted wave Born approximation (DWBA) with inclusion of RPA correlations [8]. The results there found are surprising: the low values for \( R_L/R_T \) appear to be due to a large excess of strength in the transverse channel, up to a factor 2 larger than the DWBA calculation, with or without RPA correlations, at the highest momentum. In the spin-longitudinal channel one sees some crude agreement between the data and the calculations, although the DWBA model performs too poorly to allow one to draw definite conclusions about the presence of RPA effects. Indeed, the model fails in reproducing both the momentum dependence of the strength and the position of the QEP.

It is the aim of the present letter to show how a model, developed in Ref. [9], based on Glauber theory and accounting for certain classes of many-body correlations, is able to give a fairly good description of the spin-longitudinal data, hinting at some evidence of pionic RPA effects. Moreover, while the spin-transverse data remain still unexplained, we show how the two-step mechanism, in spite of its sizable contribution in this channel, is insufficient to provide an explanation of the discrepancy.

We now briefly sketch the formalism; for further details the reader is referred to Ref. [9]. The basic quantity in the calculation of the nuclear response functions is the polarization propagator, which reads

\[
\Pi_\alpha(q, q'; \omega) = \sum_{n \neq 0} \langle \psi_0 | \hat{O}_\alpha(q) | \psi_n \rangle \langle \psi_n | \hat{O}_\alpha^\dagger(q') | \psi_0 \rangle \times \left[ \frac{1}{\hbar\omega - (E_n - E_0) + i\eta} - \frac{1}{\hbar\omega + (E_n - E_0) - i\eta} \right],
\]

where \( \{ | \psi_n \rangle \} \) is a complete set of nuclear eigenstates of energy \( E_n \) and \( \hat{O}_\alpha(q) \) the second quantized expression of the vertex operator. In the case of the spin-isospin modes one has

\[
O_L(q, r) = \tau_\alpha \sigma \cdot \hat{q} e^{iq\cdot r}
\]

\[
O_T(q, r) = \frac{\tau_\alpha}{\sqrt{2}} \sigma \times \hat{q} e^{iq\cdot r}
\]

in the longitudinal and transverse channels, respectively.

After an angular momentum expansion, the responses are defined as

\[
R_{L,T}(q, \omega) = -\frac{1}{4\pi^2} \text{Im} \sum_J (2J + 1) \Pi_{J(L,T)}(q, q; \omega),
\]

where \( \Pi_{J(L,T)} \) are obtained in the continuum RPA by solving a set of coupled integral equations, using Woods-Saxon wave functions for the ph states and the \( g' + \pi + \rho \) model for the ph interaction (in the calculations we present below, \( g' = 0.7 \) has been used).
Another important feature of the nuclear dynamics is represented by the spreading width of the ph states, i.e. by their coupling to more complicated configurations. We incorporate this element in a phenomenological manner, by including in the mean field polarization propagator a ph self-energy, designed to fit the empirical particle widths (see also Ref. [11]). Note that it turns out to be rather easy to accommodate the spreading width in our scheme, since all calculations are performed in momentum space, although we are dealing with finite systems.

Another relevant aspect of our approach is the reaction mechanism. This has been implemented in the framework of the Glauber theory [12], including one- and two-step terms: the one-step contribution is obtained by substituting the vertex operators (5) with

$$O_{L,T}(q,r) = \frac{1}{(2\pi)^2 f_{L,T}(q)} \int db d\lambda e^{-\tilde{\sigma}_{tot}(b)/2} e^{i(q-\lambda)b} f_{L,T}(\lambda) O_{L,T}(\lambda, r),$$

where $f_{L,T}$ are the elementary isovector spin-longitudinal and spin-transverse NN scattering amplitudes.

The two-step contribution has been evaluated through the convolution of two free response functions [13], i.e.

$$R^{(2)}_{L,T}(q,\omega) = \frac{D_2}{k^2 |f_{L,T}(q)|^2} \int dq' \int_0^{\omega} d\omega' |f_{L,T}(q')|^2 R_{L,T}(q',\omega') f_{00}(|q-q'|)|^2 R_{00}(|q-q'|,\omega-\omega'),$$

where $R_{00}$ and $f_{00}$ are the scalar-isoscalar nuclear response and NN amplitude, respectively, and

$$D_2 = \frac{1}{2} \int db T^2(b) e^{-\tilde{\sigma}_{tot}(b)}$$

is connected to the effective number of pairs participating in the double scattering process.

In Fig. the calculated spin-longitudinal responses are compared to the data. It is immediately apparent that the model gives a good description of the data up to 100÷150 MeV of excitation energy, depending on the angle.

At momentum transfers around 1.2 fm$^{-1}$ ($\theta = 12.5^\circ$) the longitudinal ph interaction is rather small and both the uncorrelated and RPA results well reproduce the QEP shape and strength. At $\theta = 18^\circ$ the RPA calculation works quite well on the left side of the QEP, whereas on the right the RPA and free responses are very close and slightly overestimate the strength. At $\theta = 27^\circ$, again the RPA model is quite accurate on the left of the QEP, whereas on the right the data show a faster decrease than predicted by both the RPA and the uncorrelated calculations. The two-step contribution is very small at the lowest angle and $\sim 5\%$ of the total at $\theta = 27^\circ$.

It should be noted that the low energy part of the spectra is where the present model is expected to be more reliable, since other aspects of the nuclear dynamics not included here (two-particle–two-hole (2p2h), meson production, ...) are of importance at higher energies. Moreover, at the highest momenta effects from relativistic kinematics start to be appreciable (at $q = 2.5$ fm$^{-1}$ the QEP position is shifted downward of $\approx 8$ MeV).

Note also that an important role in yielding the right shape to the quasielastic response is played by the spreading width of the ph states: as discussed in Ref. [9], the effect of
FIG. 1. Spin-longitudinal isovector responses for ($\vec{p},\vec{n}$) reactions at 494 MeV, with (solid) and without (dotted) RPA correlations. The two-step contribution is also displayed separately (dashed). Data are from Ref. [3].
FIG. 2. Spin-transverse isovector responses for $(\vec{p},\vec{n})$ reactions at 494 MeV. The meaning of the lines is explained in Fig. 1. Data are from Ref. [3].
the latter amounts to redistribute the strength around the QEP, increasing the response in
the high and low energy regions, while reducing it at the peak. A much smaller, but still
appreciable, increase of the response in the high and low energy tails is also due to the fact
that the calculations have been performed at fixed scattering angle, which accounts for the
dependence of the momentum transfer on the energy loss.

Next, we consider the spin-transverse responses, displayed in Fig. 2. Here the situation
is rather surprising: the data show, in fact, a large excess of strength in this channel, which
is the same entering in magnetic (e,e') scattering. In the latter case, the data point to a
quenching of the free response, which is indeed obtained in models based on the
$g' + \pi + \rho$
residual interaction [14].

The same quenching is also present in the RPA responses displayed in Fig. 2, in strong
contradiction with the data. In this channel the two-step contribution is much more sizable,
about 20-30% of the ph response at $\theta = 27^\circ$, but still unable to fill the gap. Describing
the data within a RPA framework would require a ph interaction radically different from the
one currently accepted; on the other hand, it is difficult to imagine that dynamical effects
such as 2p2h excitations should play a role comparable to, and even larger than, the one
they have in (e,e') scattering, since in the present case the incident proton actually probes
a lower nuclear density.

From the analysis of Figs. 1 and 2, we derive the following observations:

The spin-longitudinal response is well described in the energy domain where a ph based
model can be expected to be reliable. Note that all the ingredients entering into the cal-
culations are of importance and none can be neglected. This is true over a wide range
of momentum transfers; in particular, when the pion driven ph force is felt, then the RPA
correlations remarkably improve the description. Of course, before drawing any definite con-
clusion the effect of all the elements not included in the present model, such as $\Delta$ degrees
of freedom, 2p2h, ..., should be assessed.

On the other hand, the excess of strength in the spin-transverse response is unexplained.
As we have seen, multiple scattering is sizable and cannot be neglected, but it is not enough
to fill the gap. However, owing to the accuracy achieved in the description of the longitudinal
response, it is very unlikely that the discrepancy found in the transverse channel arises from
uncertainties in the reaction mechanism (in addition, one should note that the model gives
a good description of the $(p,p')$ cross sections as well [3]). This excess of transverse strength
is probably also responsible for the excess of cross section found in the $(p,n)$ reaction at 800
MeV [9].

On the theoretical side, it would be interesting to understand the poor performance of
the DWBA calculations [3], since the results obtained in this model are expected to coincide,
in the eikonal limit, with those obtained in the Glauber approximation.
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