Quenching of spin-dipole strength in ^{40}Ca

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A recent proton scattering experiment performed with 500 MeV protons has demonstrated a systematic quenching of the isovector spin-dipole strength. This report describes two mechanisms which can each contribute to the quenching: the effect of 2p-2h ground-state correlations and the spreading width that arises from the coupling of 1p-1h to 2p-2h excitations. The contributions from both effects bring theory within the range of experimental observation and indicate that these effects should be included in future calculations in which the origin of inhibition of spin-dependent excitations needs to be understood.

Spin-dipole resonances have recently been the focus of a great deal of theoretical and experimental attention. On the theoretical side, one expects to learn from $S=1$ resonances about the properties of the spin-dependent part of the nuclear interaction. Experimentally, information on spin-dipole resonances is still rather sparse, although a recent experiment by Horen *et al.*¹ has provided the first quantitative assessment of spin-dipole strength distribution in a $T=0$ nucleus. The reaction used was $^{40}\text{Ca}(p,p')$ performed at the Los Alamos Meson Physics Facility (LAMPF) with 500 MeV protons. In general, the agreement between (p,p') and previously measured (p,n) spectra was quite good in both shape and magnitude, and, by comparison with a recent polarized proton beam experiment at 319 MeV, evidence was also found for spin-dipole strength around 18 MeV.² More importantly, evidence was found for *systematic quenching* of spin dipole strength compared to uncorrelated 1p-1h shell model calculation performed in a $1\hbar\omega$ basis. For instance, the cross section measured at $\theta=3.5^\circ$ in the interval 13–18 MeV ascribed to $L=1$, spin-dipole strength was $(d\sigma/d\Omega)(3.5^\circ)=5.1\pm 1.3$ mb/sr, which was compared to a calculated $S=1$ strength of 7.8 mb/sr giving a quenching ratio of $(68\pm 17)\%$. Furthermore, although nearly 40% of the isovector 2^- strength was sustained in a single state at 8.4 MeV, the observed cross section at

this energy was only 25% of the calculated 1p-1h value.

The shell model calculations used for reference did not include ground-state correlations, and Horen *et al.* speculated that this omission might be at the origin of the discrepancy with experiment. It is the purpose of this Brief Report to examine this point in detail, providing calculations of 2p-2h correlations and assessing their degree of importance. In addition, we find that another mechanism, equally as important as ground-state correlation, is at play here having to do with the coupling of the 1p-1h states to 2p-2h excitations. It is, in our view, the contribution of these two excitation processes that has to be invoked to bring shell model results within calling distance of experiment.

We first examine the effect of 2p-2h ground-state correlations using the perturbation theory on the ground-state wave functions. Such an approach has already been advocated by Sagawa and Brown³ in their calculation of beta decay in mass 12.

We first write the spin-dipole transition operators that excite states with spin and parities of $0^-, 1^-, 2^-$ as

$$T_{\lambda\mu} \equiv \sum_i r_i [Y_{l=1}(\hat{r}_i) \otimes \sigma_i]_{\lambda\mu} \tau_{-1}, \quad \lambda=0, 1, 2. \quad (1)$$

The particle-hole reduced matrix elements for these tensor operators are

$$\begin{aligned} \langle (j_h^{-1} j_p) \lambda \| r [Y_l \otimes \sigma]_{\lambda} \| 0 \rangle &= \left[\frac{2j_h + 1}{4\pi} \right]^{1/2} (j_h \frac{1}{2} \lambda 0 | j_p \frac{1}{2}) \langle l_p | r | l_h \rangle \\ &\times \begin{cases} 1 & \text{for } \lambda=0, \\ - \left[\frac{2\lambda + 1}{\lambda(\lambda + 1)} \right]^{1/2} [(-1)^{l_p + 1/2 - j_p} (j_p + \frac{1}{2}) - (-1)^{l_h + 1/2 - j_h} (j_h + \frac{1}{2})] & \text{for } \lambda=1, \\ \sqrt{\lambda} [1 + (-1)^{l_p + 1/2 - j_p} (j_p + \frac{1}{2}) + (-1)^{l_h + 1/2 - j_h} (j_h + \frac{1}{2})] & \text{for } \lambda=2. \end{cases} \quad (2) \end{aligned}$$

The ground-state correlations that we include are represented diagrammatically by Fig. 1. Including such correlations allows the modified ground-state wave function to be written in first-order perturbation theory as

$$|\tilde{0}\rangle = |0\rangle + \sum_{\substack{php'h' \\ J}} \frac{\langle (ph^{-1}J, (p'h'^{-1})J; 0^+ | V | 0^+ \rangle}{E_0 - E_J(php'h')} |(ph^{-1}J, (p'h'^{-1})J; 0^+ \rangle. \quad (3)$$

FIG. 1. A diagrammatical representation of 2p-2h ground-state correlations is shown.

With this perturbed state vector, the modified transition strength can be defined by the parameter α , where

$$\langle (ph^{-1})\lambda \| T_\lambda \| \tilde{0} \rangle = \langle (ph^{-1})\lambda \| T_\lambda \| 0 \rangle (1 - \alpha) \quad (4)$$

and

$$\alpha \equiv \sum_{p'h'} \frac{\langle (ph^{-1})\lambda \| V | (p'h'^{-1})\lambda \rangle \langle (p'h'^{-1})\lambda \| T_\lambda \| 0 \rangle}{E_\lambda(ph, p'h') - E_0 \langle (ph^{-1})\lambda \| T_\lambda \| 0 \rangle} \quad (5)$$

The calculations of α were then carried out using harmonic-oscillator wave functions and a simple δ interaction including a spin-exchange operator based on the Skyrme III force⁴

$$V(\mathbf{r} - \mathbf{r}') = t_0(1 + \chi_0 P^\sigma) \delta(\mathbf{r} - \mathbf{r}')$$

with

$$P^\sigma = \frac{1}{2}(1 + \boldsymbol{\sigma} \cdot \boldsymbol{\sigma}').$$

With such an interaction it becomes straightforward to calculate the matrix elements of the potential (see Refs. 5 and 6). The results of the calculations of α are tabulated in Table I. It is immediately apparent that the transition strength from most of the states are substantially decreased by the perturbation due to 2p-2h mixing.

We now consider a different process: namely, the coupling of p - h to 2p-2h excitations, which is at the origin of the spreading width acquired by the resonance states. We have already studied the importance of such an effect in a recent analysis of proton inelastic scattering experiment.⁷ The origin of the spreading width has also been

TABLE I. Effect of 2p-2h ground-state correlations on $T=1$ 1p-1h states. The parameter α is used to define the modification of the transition strength, $\langle (ph^{-1})\lambda \| T_\lambda \| \tilde{0} \rangle = \langle (ph^{-1})\lambda \| T_\lambda \| 0 \rangle (1 - \alpha)$.

p - h state	α		
	$\lambda^\pi = 2^-$	$\lambda^\pi = 1^-$	$\lambda^\pi = 0^-$
$(1f_{7/2} 1d_{5/2}^{-1})$	-0.081	0.109	
$(2p_{3/2} 1d_{5/2}^{-1})$	0.054	0.258	
$(1f_{5/2} 1d_{5/2}^{-1})$	0.373	0.034	0.259
$(2p_{1/2} 1d_{5/2}^{-1})$	0.060		
$(2p_{3/2} 2s_{1/2}^{-1})$	-0.024	0.249	
$(1f_{5/2} 2s_{1/2}^{-1})$	0.212		
$(1f_{7/2} 1d_{3/2}^{-1})$	0.169		
$(2p_{3/2} 1d_{3/2}^{-1})$	0.202	0.043	0.059
$(1f_{5/2} 1d_{3/2}^{-1})$	0.151	0.225	
$(2p_{1/2} 1d_{3/2}^{-1})$	0.114	0.082	
$(2p_{1/2} 2s_{1/2}^{-1})$		-0.065	0.252

FIG. 2. A diagrammatic representation of the particle-hole decay width, Γ^{ST} , is shown. Diagrams (a) and (b) correspond to particle and hole decay, respectively, while (c) denotes the interference term.

discussed in some detail by Smith and Wambach.⁸ Microscopically, the processes responsible for the 2p-2h spreading width are shown in Fig. 2.

The total width, Γ^{ST} , can be obtained from the imaginary part of the optical potential and the hole widths. Assuming that the optical potential is symmetric about the Fermi energy and denoting the (a) and (b) parts of diagrams (1) and (2) by Γ_p and Γ_h , the total width can be expressed as

$$\Gamma^{\text{ST}}(\omega) = \frac{1}{\omega} \int_0^\omega d\epsilon [\Gamma_p(\epsilon) + \Gamma_h(\epsilon - \omega) + 2C^{\text{ST}} \sqrt{\Gamma_p(\epsilon)\Gamma_h(\epsilon - \omega)}] \quad (7)$$

Thus, $\Gamma^{\text{ST}}(\omega)$ is completely specified by single-particle data once C^{ST} is calculated; this produces an energy-dependent width that corresponds to asymmetric peaks. The effect of this asymmetry is to push strength to higher energies. In any given energy region, such as the 13 to 18 MeV region discussed by Horen *et al.*, there is some extra strength gained from states lying below the energy of the region, while some strength from states lying within the region is pushed to higher energy. Since the width increases with energy, proportionately more strength is pushed out of the region than into it, resulting in an overall quenching of the strength in the energy region considered.

In the fourth column of Table II, we present the quenching results obtained for different energy regions when both mechanisms (i.e., configuration mixing and spreading width) are included. In the energy range $13 \leq E_x \leq 18$ MeV, the results are very compatible with the experimental quenching factor of 0.68 ± 0.17 . In the higher-energy range of $18.5 \leq E_x \leq 21.5$ MeV, the low cross section can also be understood as a consequence of these two effects. It is also noted that the coupling of the two effects is not pure (i.e., $\Delta_{\alpha+\Gamma} \neq \Delta_\alpha \Delta_\Gamma$). This is due to

TABLE II. Quenching factors due to spreading width (Δ_Γ), ground-state correlation (Δ_α), and a combination of the two effects ($\Delta_{\Gamma+\alpha}$).

Energy range (MeV)	Δ_Γ	Δ_α	$\Delta_{\Gamma+\alpha}$	$\Delta_{\Gamma+\alpha}/\Delta_\alpha$
8-13	0.66	0.80	0.53	0.66
13-18	0.71	0.87	0.60	0.69
18-21.5	0.78	0.79	0.62	0.77
≥ 21.5	0.89	0.72	0.69	0.96

the energy dependence of Γ : at the highest energies, the quenching is almost solely due to the ground-state correlation, as any strength lost to lower energies by the spreading width is compensated by strength from lower-lying states.

It should also be noted that the relative cross section of the 8.4 MeV, 2^- state is 0.70 when the ground-state correlations are included. It is 0.25 when the spreading width alone is introduced, and drops to 0.18 when the two effects are combined. This result is very consistent with the factor of 0.25 obtained in the inelastic proton scattering experiment of Horen *et al.*

Finally, in the 18.0–21.5 MeV energy region, Horen *et al.* comment on the fact that the measured cross section appears to be lower than would be expected if the $S=1$ and $S=0$ components were to add *incoherently*. In fact, in the two states where there is appreciable mixing between $S=1$ and $S=0$ states (at 14.7 and 20.1 MeV), we find, on the contrary, *a large degree of coherence*. Since the interaction is repulsive in both channels, this could

account at least in part for the rather low experimental cross section seen in this higher-energy range.

In conclusion, we have examined in detail two effects that can each account, in part, for the observed quenching of spin-dipole strength in ^{40}Ca . Each effect modifies the cross section in a substantial manner. The first is due to 2p-2h ground-state correlations, which result in a decrease in the overall strength of each state. The second is the coupling of 1p-1h to 2p-2h excitations, which produces an asymmetric, energy dependent width for the states. The importance of these coupling mechanisms certainly indicates that they should be included in calculations in the future, especially when the emphasis is on understanding the origin of inhibition of spin-dependent excitations.

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