EFFECTS OF TWO-PARTICLE–TWO-HOLE GROUND-STATE CORRELATIONS ON SPIN-DIPOLE TRANSITIONS IN ^{12}N

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We have studied the effect of two-particle–two-hole ground-state correlations on the spin-dipole transitions in ^{12}N. We found that the transition strengths in the energy range E_x = 2–12 MeV are quenched 25% by the ground state correlations. The tensor correlation is important for 1^- and 2^- states, while the spin–orbit force has an appreciable effect on 1^- states only.

The (p, n) reaction at intermediate energy is an extremely useful probe for the study of $\sigma \cdot \tau$ correlations in nuclei [1]. The cross section at zero degrees has been studied in detail and the Gamow–Teller (GT) strength for $l = 0$ transition has been extracted systematically in many nuclei throughout the periodic table [1,2]. Moreover, the neutron spectra at larger angles ($\theta = 5$–$15°$) show strong transitions characterized by $l = 1$ angular distributions with a large width of around 10 MeV for nuclei $A \geqslant 40$ [1]. These broad resonances are interpreted by an envelope of collective states with spin parities 2^-, 1^- and 0^- excited through the transition operators [3],

$$T_{\lambda\mu} = \sum_i r_i \left[Y_{l=1}(\hat{r}_i) \times \boldsymbol{\sigma}_i \right]_{\lambda\mu} \tau_{-1}, \quad \lambda = 2^-, 1^-, 0^-. \tag{1}$$

We refer to them as spin-dipole transition operators. The particle–hole matrix elements for these operators are given by

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

It has not been possible to resolve the broad peaks at angles ($\theta = 5$–$15°$) in heavy nuclei into their components and confirm each transition strength partly due to the poor energy resolution of neutron spectra. Recently, in the light nucleus ^{12}N, the spin-dipole states with $\lambda^\pi = 1^-, 2^-$ have been observed separately in the energy region E_x = 2–12 MeV [4]. From the experimental neutron spectrum for the ^{12}C(p, n)^{12}N reaction at $E_p = 160$ MeV and $\theta = 8°$, the extracted cross section obtained by adding the total yield (corrected for cosmic ray background) is given by

$$\sum_{E_x} \frac{d\sigma}{d\Omega} (E_x = 2\text{–}12 \text{ MeV})_{\text{exp}} = (12.0 \pm 1.8) \text{mb/sr}, \tag{3}$$

while a shell-model calculation [4] gives the summed cross section,

$$\sum_{E_x} \frac{d\sigma}{d\Omega} (E_x = 2\text{–}12 \text{ MeV})_{\text{theory}} = 20 \text{ mb/sr}. \tag{4}$$

The model prediction in ref. [4] took into account one-particle–one-hole (1p–1h) states built on the lowest six odd-parity states of the $A = 11$ system and the excitations from the $0s_{1/2}$-orbit were not allowed.

Table 1
Sum rule values $B(l=1, \lambda^{\pi})$ for the spin-dipole transitions in ^{12}N. The values in row 1 are obtained by the 1p–1h excitations from $0p_{3/2}$- and $0s_{1/2}$-states assuming a $0p_{3/2}$-closed shell. The shell-model calculation of ref. [4] in row 2 took into account only 1p–1h excitations from the lowest six odd-parity states of the $A=11$ system, while the present calculation in row [3] includes all configurations from 0p- and 0s-orbits. For details, see the text.

	λ^{π}		
	0^-	1^-	2^-
1p–1h	5.56	14.11	14.97
ref. [4]	3.79	10.76	16.03
present	4.56	12.61	17.48
ref. [4] ($E_x \leqslant 12$ MeV)	3.34	9.70	15.00
present ($E_x \leqslant 12$ MeV)	2.69	8.60	14.67
ref. [4] ($E_x \leqslant 18$ MeV)	3.79	10.76	16.03
present ($E_x \leqslant 18$ MeV)	3.63	9.97	15.80

We show in table 1 the results of a full 1 $\hbar\omega$ 1p–1h configuration space calculation based on the Cohen–Kurath wave function for the $A=11$ system in comparison with the result of ref. [4]. A Yukawa-type potential with central, spin–orbit and tensor components is used for the present calculation;

$$V(r) = V_c(r) + V_{LS}(r) + V_T(r),$$
$$V_c(r) = V_c\left(a_c^{11}P^{11} + a_c^{31}P^{31} + a_c^{13}P^{13} + a_c^{33}P^{33}\right) \times (\mu_c/r)\exp(-r/\mu_c),$$
$$V_{LS}(r) = V_{LS}\left(a_{LS}^{13}P^{13} + a_{LS}^{33}P^{33}\right)\boldsymbol{L}\cdot\boldsymbol{S}(\mu_{LS}/r) \times \exp(-r/\mu_{LS}),$$
$$V_T(r) = V_T\left(a_T^{13}P^{13} + a_T^{33}P^{33}\right)S_{12}(\mu_T/r) \times \exp(-r/\mu_T), \tag{5}$$

where $P^{2T+1,2S+1}$ is the projection operator of the (T, S) channel and S_{12} is the tensor operator. We

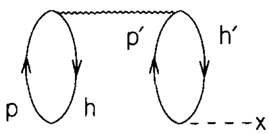

Fig. 1. Diagrammatical representation of the 2p–2h ground-state correlation.

adopted the parameter set of Millener and Kurath [5] which is listed in table 2. The summed cross section $d\sigma/d\Omega$ ($E_x = 2$–12 MeV) for the present calculation is 19 mb/sr compared to 20 mb/sr obtained in the restricted space calculation [4]. Both calculations show about 10% of the total transition strengths in the energy region $E_x = 12$–18 MeV. However, the full space calculation shows 15% of the total strength above $E_x = 18$ MeV, while there is no transition strength in this region in the calculation of ref. [4].

We study in this letter the effect of 2p–2h ground-state correlations on the spin-dipole transitions in ^{12}N using perturbation theory. The 2p–2h correlation is claimed as an important effect for the quenching of magnetic dipole and Gamow–Teller transition strengths in recent microscopic calculations [6,7]. The ground-state correlation is shown diagrammatically in fig. 1. The first-order perturbation theory gives the following wave function;

$$|\tilde{0}\rangle = |0\rangle + \sum_{\substack{ph,p'h' \\ J}} \frac{\langle (ph^{-1})J, (p'h'^{-1})J; 0^+|V|0^+\rangle}{E_0 - E_J(ph, p'h')} \times |(ph^{-1})J, (p'h'^{-1})J; 0^+\rangle. \tag{6}$$

Using this perturbed wave function (6), we obtain the modified transition strength,

$$\langle (ph^{-1})\lambda \| T_\lambda \| \tilde{0}\rangle = \langle (ph^{-1})\lambda \| T_\lambda \| 0\rangle (1-\alpha), \tag{7}$$

Table 2
Interaction parameters.

	a^{11}	a^{31}	a^{13}	a^{33}	b/μ	V(MeV)
central	−0.714	0.6	1	−0.286	1.18	−44.8
tensor	0	0	1	−0.38	1.18	−16.25
spin–orbit	0	0	1	3.5	2.36	−26

where

$$\alpha = \sum_{\mathrm{p'h'}} \frac{\langle (\mathrm{ph}^{-1})\lambda | V | (\mathrm{p'h'}^{-1})\lambda \rangle}{E_\lambda(\mathrm{ph},\mathrm{p'h'}) - E_0} \langle (\mathrm{p'h'}^{-1})\lambda \| T_\lambda \| 0 \rangle. \tag{8}$$

We calculate the particle–hole (p–h) matrix elements with the Yukawa-type potential with central, spin–orbit and tensor components as given in eq. (5). The p–h energy difference is taken to be 15.4 MeV. The oscillator length is determined as $b = 1.64$ fm in order to reproduce the mean charge radius of ^{12}C.

The calculated values of α are given in table 3. The central interaction gives $\alpha = 0.13$ which decreases the spin-dipole transition strength by about 25%. This positive value of α is due to the fact that the spin–isospin p–h interaction is repulsive. We also calculated α by using the parameter set for the central interaction given by Ferrell and Visscher [8]. This gave a slightly larger value of $\alpha = 0.15$.

The tensor correlation increases the values of α for the state with $\lambda^\pi = 1^-$ by 10–20%, while decreasing the value of α for $\lambda^\pi = 0^-$ by about the same amount. The transition strength of the 2^- state is not changed much by the tensor correlation. This result can be understood intuitively by the following argument given by Mottelson [9].

The tensor interaction can be given in the form

$$V_{\mathrm{T}}(r) = F(r)\left\{ [\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2]^{(2)} \times [r^2 Y_2(\hat{r})]^{(2)} \right\}^{(0)}. \tag{9}$$

Since the solid spherical harmonics $r^2 Y_{2m}(\hat{r})$ can be expanded by the formula

$$r^2 Y_{2m}(\hat{r}) = \sum_{\lambda'\mu'} \sqrt{4\pi}\,(-)^{\lambda'} \times [5!/(2\lambda'+1)!(5-2\lambda')!]^{1/2} \times \langle 2-\lambda'\ \lambda'\ m-\mu'\ \mu' | 2\ m \rangle r_1^{2-\lambda'} r_2^{\lambda'} \times Y_{2-\lambda',m-\mu'}(\hat{r}_1) Y_{\lambda'\mu'}(\hat{r}_2), \tag{10}$$

the tensor interaction (9) can be expressed in terms of the spin-dipole operators,

$$V_{\mathrm{T}}(r) = F(r) \sum_{\lambda} (-)\tfrac{1}{6}\sqrt{4\pi}\,(\tfrac{10}{3})^{1/2} \begin{Bmatrix} 2\sqrt{5} \\ -\sqrt{15} \\ 1 \end{Bmatrix} \times \left\{ r_1 [\boldsymbol{\sigma}_1 \times Y_1(\hat{r}_1)]^{(\lambda)} \times r_2 [\boldsymbol{\sigma}_2 \times Y_1(\hat{r}_2)]^{(\lambda)} \right\}^{(0)},$$

$$\lambda^\pi = \begin{Bmatrix} 0^- \\ 1^- \\ 2^- \end{Bmatrix}, \tag{11}$$

where we choose $\lambda' = 1$ only in the expansion (10). Since the coupling strength $F(r)$ is repulsive for the tensor interaction, the tensor correlation for the 1^- state is additive to that of the central interaction. On the other hand, the two contributions tend to cancel each other in the case of the 0^- state. A smaller tensor correlation for the 2^-

Table 3
Normalization factors α for spin dipole transitions.

λ^π	(p–h)	$\langle (\mathrm{h}^{-1}\mathrm{p})\lambda \| T \| 0\rangle$	$\alpha(V_{\mathrm{C}})$	$\alpha(V_{\mathrm{C}}+V_{\mathrm{T}})$	$\alpha(V_{\mathrm{C}}+V_{\mathrm{T}}+V_{\mathrm{LS}})$
0^-	$(2s1/2, 1p1/2^{-1})$	−0.654	0.093	0.077	0.077
	$(1d3/2, 1p3/2^{-1})$	1.463	0.135	0.095	0.095
1^-	$(1d3/2, 1p1/2^{-1})$	1.035	0.135	0.158	0.133
	$(2s1/2, 1p1/2^{-1})$	0.925	0.093	0.101	0.116
	$(1d3/2, 1p3/2^{-1})$	1.851	0.135	0.154	0.147
	$(1d5/2, 1p3/2^{-1})$	−1.388	0.135	0.156	0.180
	$(2s1/2, 1p3/2^{-1})$	0.654	0.093	0.101	0.072
2^-	$(1d3/2, 1p1/2^{-1})$	−0.463	0.135	0.085	0.089
	$(1d5/2, 1p1/2^{-1})$	2.266	0.135	0.133	0.133
	$(1d3/2, 1p3/2^{-1})$	−0.925	0.135	0.145	0.147
	$(1d5/2, 1p3/2^{-1})$	2.120	0.135	0.129	0.127
	$(2s1/2, 1p3/2^{-1})$	1.463	0.093	0.091	0.091

state is also quite reasonable since the coefficient for 2^- in eq. (11) is several times smaller than those for 0^- and 1^-. The results given in table 3 are slightly different from that expected from eq. (11) because of the exchange term contribution.

As can be seen in the last column of table 3, the spin–orbit two-body force has an appreciable effect only on 1^- states. The spin–orbit two-body operator is given by

$$\boldsymbol{L} \cdot \boldsymbol{S} = \tfrac{1}{2}(\boldsymbol{r}_1 - \boldsymbol{r}_2) \times (\boldsymbol{p}_1 - \boldsymbol{p}_2) \cdot (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2). \quad (12)$$

When eq. (12) is expanded in terms of the spin-dipole operators, the important terms for the direct two-body matrix elements in eq. (8) are

$$\boldsymbol{L} \cdot \boldsymbol{S} \propto r_1 \left\{ \left[\boldsymbol{\sigma}_1 \times Y_1(\hat{r}_1) \right]^{(1)} \times \boldsymbol{p}_2 \right\}^{(0)} + r_2 \left\{ \left[\boldsymbol{\sigma}_2 \times Y_1(\hat{r}_2) \right] \times \boldsymbol{p}_1 \right\}^{(0)}, \quad (13)$$

where the spin-dipole operator can couple to $\lambda^\pi = 1^-$ only. This is the reason why the spin–orbit force contributes appreciably to the value of α for the states with $\lambda^\pi = 1^-$, but not for the states with $\lambda^\pi = 0^-$ and 2^-.

In summary, we have studied the effect of the 2p–2h ground state correlation on the spin-dipole transition in ^{12}N. We found that the net effect of the central, tensor and spin–orbit forces, averaging over the transition matrix elements, gives the values $\alpha = 0.089$, 0.139 and 0.122 for $\lambda^\pi = 0^-$, 1^- and 2^-, respectively. Because the experimental data in the region $E_x = 2$–12 MeV is dominated by 1^- and 2^- resonances, the value α substantially decreases the spin-dipole transition strength by about 25%. The tensor correlation contributes 10–20% to the renormalization factors α for 0^- and 1^- states, while the 2^- state is insensitive to the tensor force, the effect of the two-body spin–orbit correlation is appreciable only in the transition strength of the 1^- state. The experimental cross section in the energy region $E_x = 2$–12 MeV is 40% less than the 1p–1h shell-model prediction in the full configuration space and the present study suggests that the 2p–2h ground-state correlations explain the major part (60%) of this missing strength. The transition strengths might be decreased further by meson-exchange currents [7] and Δ-hole couplings [10] together with higher 2p–2h excitations above $1\hbar\omega$ configuration space [5].

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References

[1] C. Gaarde et al., Nucl. Phys. A369 (1981) 258.
[2] D.J. Horen et al., Phys. Lett. 95B (1980) 27;
C. Goodman, Nucl. Phys. A374 (1982) 241c;
C. Gaarde, Nucl. Phys. A396 (1983) 127c.
[3] F. Osterfeld et al., Phys. Lett. 105B (1981) 257.
[4] C. Gaarde et al., Nucl. Phys. A422 (1984) 189.
[5] D.J. Millener and D. Kurath, Nucl. Phys. A255 (1975) 315.
[6] G.F. Bertsch and I. Hamamoto, Phys. Rev. C26 (1982) 1323.
[7] I.S. Towner and F.C. Khanna, Phys. Rev. Lett. 42 (1979) 51;
A. Arima et al., Phys. Lett. 122B (1983) 126.
[8] W.M. Visscher and R.A. Ferrell, Phys. Rev. 107 (1957) 781.
[9] B.R. Mottelson, private communication.
[10] H. Toki and W. Weise, Phys. Lett. 97B (1980) 72;
T. Suzuki, C. Gaarde and H. Sagawa, Phys. Lett. 116B (1982) 91.