Theoretical interpretation of the Gamow-Teller strength in the ^{42}Ca$(p,n)^{42}$Sc reaction

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We have calculated the Gamow-Teller strength of the ^{42}Ca$(p,n)^{42}$Sc(1^+) reaction using the Kuo-Brown wave function. This shell model calculation together with the Δ isobar quenching mechanism accounts for the Gamow-Teller strength.

[NUCLEAR STRUCTURE Shell model, reaction matrix, GT strength, Δ isobar polarization.]

Recently, Goodman *et al.* have performed a (p,n) experiment on ^{42}Ca with the proton energy $E_p=160$ MeV.[1] In their neutron forward angle spectrum ($\theta=0°$) they found a strong peak at the excitation energy $E_x=0.6$ MeV and very weak strengths at higher excitation energy. All these peaks were identified as $J^\pi=1^+$ states due to the strong preference of spin-isospin excitation of high energy proton.[2,3] This data has to be contrasted with the 0° neutron spectrum of the ^{48}Ca$(p,n)^{48}$Sc reaction, where most of the Gamow-Teller (GT) strength is found in the region between $E_x=5-10$ MeV and only ~20% of that is seen at the lowest 1^+ state.[4] All heavier nuclei studied so far show the same features in the Gamow-Teller strength function as is seen in ^{48}Sc.

In order to understand this result on ^{42}Sc, Goodman *et al.* suggest that the ground state of ^{42}Ca might be more nearly characterized by $L=0$, $S=0$, and $T=1$ [U(4) symmetry] than is implied by $(f_{7/2})^2J=0$.[1] This is because the operation of the Gamow-Teller operator, $\sum\sigma\tau_-$, on the U(4) symmetry state yields only the $L=0$, $S=1$, and $T=0$ state and nothing else, as is found in the experiment. It is true that the eigenfunction taking into account the realistic aspects of shell model such as the large spin-orbit splitting between the $f_{5/2}$ and $f_{7/2}$ states do show the tendency to the U(4) symmetry.[5] However, this happens only at a qualitative level.[5] Therefore, we have asked if this conventional shell-model approach can provide a reasonable explanation for the concentration of the GT strength in the lowest 1^+ state.

For this purpose, we take the wave functions calculated by Kuo and Brown (KB) for the $0f$-$1p$ shell nuclei.[6] These wave functions are derived from a Hamiltonian based on the Brueckner G matrix derived from the nucleon-nucleon interaction, and have demonstrated a satisfactory description of these nuclei. Reference 6 derived the G matrix from the Hamada-Johnson potential, but the use of more recent potentials such as the Reid or Paris potentials does not change the G-matrix elements appreciably.[7,8] Furthermore, the core polarization graph is taken into account for the open shell effective interaction as the most important correction to the bare reaction matrices. We prefer these KB matrix elements over the interaction[9] which is used in Ref. 1.

Let us first look at the ground state wave function of ^{42}Ca. (See Table 2 in Ref. 6.) Out of the five configurations in the model space spanned by $f_{7/2},f_{5/2},p_{3/2},p_{1/2},g_{9/2}$, the $(f_{7/2})^2$ configuration is dominating (~86%) and the $(f_{5/2})^2$ configuration is about 4% sharing about the same probabilities with the others. Therefore, the wave function is far from that of $L=0$, $S=0$, and $T=1$, which demands about equal amplitudes for $(f_{7/2})^2$ and $(f_{5/2})^2$; i.e., 57% and 43%, respectively.

Coming to the 1^+ states, we have seven states for $T=0$ and three states for $T=1$. Kuo and Brown do not tabulate all their wave functions, so we have reconstructed them by diagonalizing the Hamiltonian constructed from the interaction matrix elements given in Appendix 3 of Ref. 6. We find the Gamow-Teller strength to be distributed over the eigenstates as shown in Table I. The lowest 1^+ state takes almost the full strength among the $T=0$ states. The rest is distributed among four states with $T=0$ distributed between $E_x=4-9$ MeV. Hence, as far as $T=0$ states are concerned, the Kuo-Brown wave functions provide correct features as to the concentration of the GT strength to the lowest 1^+ state. The use of the interaction employed in Ref. 1 gives essentially the same result. If we take overlap between this lowest 1^+ state with the U(4) symmetry state, it comes out $|\langle(L=0,S=1)J=1|\text{lowest } 1^+\rangle|^2=0.64$. It means even if the ^{42}Ca ground state had the U(4) symmetry, about 36% of the GT strength would be distributed among higher 1^+ states. In fact, the $T=1$ states carry the GT strength of 0.84, which is shared by two very close states at 9.5 MeV. Note that the sum of the GT strengths does

TABLE I. Gamow-Teller strength in ^{42}Sc.

	Expt.			Theor. (Kuo-Brown)		
T	E_x (MeV)	B (GT)	T	E_x (MeV)	B (GT)	$\tilde{B}$ (GT)
0	0.6	2.67[a]	0	1.2	4.61	2.67
0	2.1	0.21	0	4 ⋮ 9	0.40	0.23
0	3.6	0.21				
(1)	10.2	0.15	1	9.5	0.84	0.49
1	(e,e') 11.2	0.34				

[a] This value is obtained from the β-decay ft value (Ref. 10) and other strengths in this column are normalized to this value.

not exhaust the sum rule value $\sum_n |\langle n | \sum_i \sigma\tau_- | 0\rangle|^2 = 6$. This is due to the omission of the $(g_{7/2}g_{9/2})_{1^+}$ configuration in the KB wave functions.

If compared with the (p,n) data normalized to the β-decay ft value,[10] the calculated GT strength seems to be too large. This is not a failure of the shell model but known as the systematic quenching of spin flip transitions, much of which may be attributed to the Δ isobar-hole dimesic polarization.[11–14] Indeed, in ^{41}Ca, the Gamov-Teller transition is hindered by ~25%. The first order perturbation computation of the Δ isobar-hole excitations leads to the quenched value 2.67 from 4.61 for the lowest state with the strength of the δ-function force of $g'=0.7$ in the definition of Toki and Weise.[14] Assuming the same quenching strength to the other GT transitions, we get the GT strengths as shown in the far right column in Table I. The agreement is reasonable.

Concerning the $T=1$ states, we would like to look at the electron scattering data on ^{42}Ca performed at Darmstadt.[15] The electron scattering experiment found the $M1$ strength at $E_x = 11.2$ MeV, which correponds to the GT strength of 0.34. If we compare now the calculated result with this value, the agreement is really satisfactory. McGrory and Wildenthal[16] as well as Goodman *et al.*[1] found the same thing. How can we understand this discrepancy between the (p,n) data (very small or not seen) and the (e,e') data? We may have to blame the (p,n) data for this, since the factor 2 may easily come from the background subtraction. However, the higher resolution (p,n) experiment at $E_p = 120$ MeV by Austin and Galonsky[17] on ^{42}Ca indicates also the small GT strength for the state around 10 MeV consistent with the (p,n) data at $E_p = 160$ MeV.[1] This difference may then come from the reaction mechanism in the hadronic reaction. In fact, Suzuki *et al.*[18] calculated ^{12}C$(p,p')^{12}$C$(T=1, 1^+)$ at $E_p = 122$ and 156 MeV and found that the cross sections with and without the exchange process (knockout) differ by about an order of magnitude even at small angles. Therefore, it is quite possible that the exchange process has different effects for different transitions, in particular, for $\Delta T = 0$ and 1 transitions in the (p,n) reaction. The factorization of the direct and exchange processes into interaction and structure factors has been demonstrated for strong transitions.[3] It is very interesting to check if such a procedure is possible also for weak transitions.

Finally, we would like to mention the cause of the apparent difference between the GT strengths in ^{42}Sc and ^{48}Sc. This is simply due to the fact that the particle-particle matrix elements (attractive and relevant for ^{42}Sc) and the particle-hole matrix elements (repulsive and relevant for ^{48}Sc) have the opposite sign. This fact suggests an interesting phenomenon to be found experimentally that the GT strength moves up gradually from the lowest state (predominantly $f_{7/2}-f_{7/2}$) to the higher state (predominantly $f_{5/2}-f_{7/2}$) as the neutron number is increased and at the middle (^{44}Sc and ^{46}Sc) the two 1^+ states share the GT strength equally and finally the higher state takes most of the strength as seen in ^{48}Sc.

In conclusion, the conventional shell-model with the theoretically sound matrix elements provides satisfactory account of the GT strength found in the ^{42}Ca$(p,n)^{42}$Sc reaction with the help of the quenching mechanism due to the Δ isobar-hole polarization.

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