VOLUME 52, NUMBER 16 PHYSICAL REVIEW LETTERS 16 APRIL 1984

Observation of Quenching in Isoscalar and Isovector $0^+ \rightarrow 1^+$ Transitions in ^{28}Si(p,p')

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(Received 28 December 1983)

Excitations of a $T=0$ and nine $T=1$, 1^+ states have been observed in the reaction ^{28}Si(p,p') at 201 MeV. The magnitudes of the measured cross sections of the isoscalar and isovector transitions are, respectively, about 24% and 33% of predictions obtained with full-basis *sd*-shell-model wave functions. The large reduction factor in the isoscalar channel, where Δ-isobar effects must be insignificant, suggests that higher-order configuration mixing must be an important source of quenching in both isoscalar and isovector channels.

PACS numbers: 25.40.Ep

Recent (p,n) measurements of Gamow-Teller (GT) transitions[1,2] and (e,e')[3,4] and (p,p')[5,6] measurements of $0^+ \rightarrow 1^+$ transitions indicate a substantial quenching of isovector spin-flip strength in the low-excitation energy region relative to shell-model predictions which take into account configuration mixing only within a single major oscillator shell. The quenching of the GT strength occurs not only for the "giant" GT transitions observed in (p,n) reactions but also for GT beta decays[7,8] between individual states. Many authors have suggested that the quenching is primarily due to Δ-isobar admixtures entering into the nuclear wave functions in first order.[9] However, other authors[10-13] suggest that configuration mixing over many oscillator quanta, mediated by the tensor force, is comparable to, or more important than, the Δ-isobar effect in producing the observed quenching.

Since the isobar-to-nucleon coupling is isovector, this mechanism is blocked from playing a significant role in isoscalar processes. Any quenching of isoscalar strength must thus be taken as strongly indicative of an important role for higher-order configuration mixing, not only in isoscalar processes but in isovector as well.[14] The only significant data to date which bears on isoscalar/isovector quenching comes from magnetic moments, where a few large quenchings are observed.[8] However, since these effects are not universal and since the most dramatic evidence for isovector quenching is found in isovector $0^+ \rightarrow 1^+$ excitations in the giant resonance region, the measurement of isoscalar $0^+ \rightarrow 1^+$ strength is crucial to resolving the issue of the source (or sources) of the quenching phenomenon.

Unfortunately, such measurements are extremely elusive. They must involve $T=0$ $(N=Z)$ targets and 1^+ final states whose $T=0$ structure is quite pure. Moreover, the conventional (e,e') and (γ,γ') probes for spin-flip excitations are based on the magnetic dipole operator, which is so dominated by its isovector component that in searches for $T=0$ states they will tend either to sample only the $T=1$ contaminants in these states or to miss them altogether. In this Letter we analyze the results of the first scattering experiment which has surmounted all of these obstacles. The data are obtained in the small-angle scattering of 201-MeV protons from ^{28}Si. This nucleus provides a $T=0$ target and a single $T=0$, 1^+ state which is strongly excited in (p,p') and which appears to be as free from mixing with $T=1$ states as any likely to be found.

The measurements were carried out with use of the magnetic spectrometer and focal plane detection system[15] of the Orsay synchrocyclotron. With a natural Si target of 8.7 mg/cm^2 thickness, an energy resolution of 60 keV was obtained. A spectrum measured at $\theta_{\text{lab}}=3.2°$ is shown in Fig. 1. By combining information obtained from an energy-level tabulation for ^{28}Si,[16] from the measured (p,p') angular distribution shapes, and from a backward-angle (e,e') measurement,[17,18] we have been able to make J^π assignments to all of the indicated peaks in Fig. 1.

The levels at 5.00, 6.72, 9.73, and 11.15 MeV are

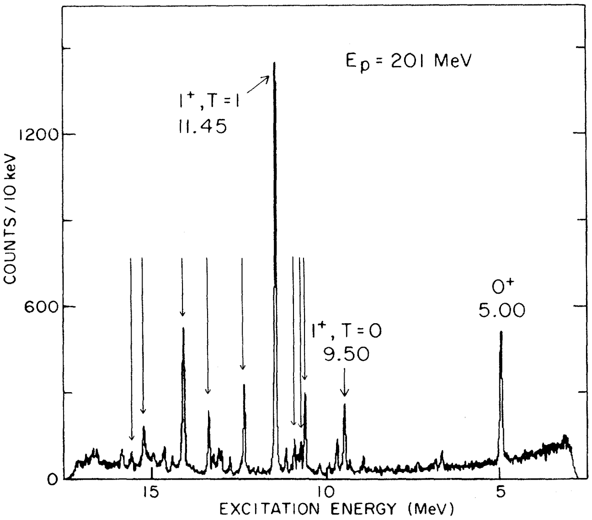

FIG. 1. Inelastic proton spectrum for ^{28}Si at 3.2°. The arrows indicate the one $T=0$ and nine $T=1$, 1^+ states observed.

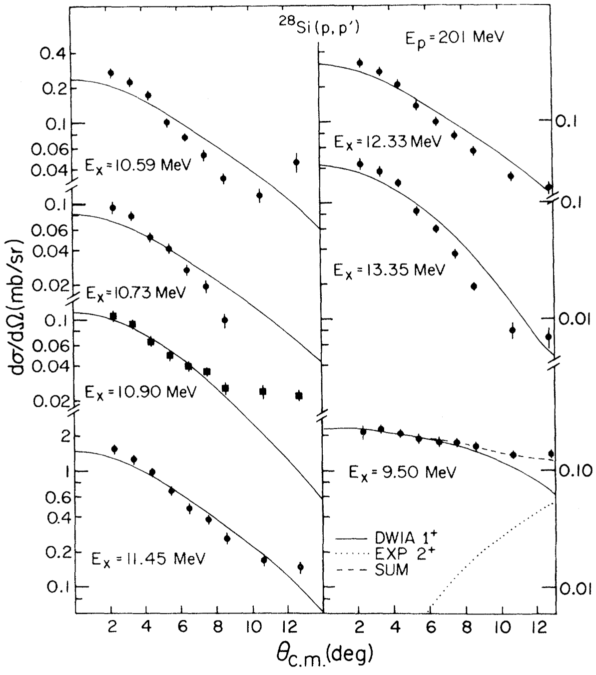

FIG. 2. Angular distributions for seven 1^+ states, one (at $E_x = 9.50$ MeV) with $T=0$ and the others with $T=1$. The solid curves are the results of DWIA calculations discussed in the text. The dotted curve for the 9.50-MeV doublet represents the experimental shape for a 2^+ state and the dashed line is the sum of the solid and dotted curves.

observed in our data to have the same angular distribution shape. Since the lower two levels are known to have $J^\pi = 0^+$, we make the same assignments to the higher two states as well. The peak at 9.50 MeV is an unresolved doublet, consisting of a known $T=0$, 2^+ level at 9.48 MeV, and a level at 9.50 MeV with $T=0$ and a J^π assignment of 1^+, 1^-, or 2^+. On the basis of its angular distribution, which is discussed below, the peak at 9.50 MeV must have $J^\pi = 1^+$. In the excitation energy range between 10.59 and 15.50 MeV, we observe the eight 1^+, $T=1$ levels known from electron scattering[17,18] and a ninth one that is not seen in (e,e'). The measured angular distributions for six of the 1^+, $T=1$ levels and for the 1^+, $T=0$ level at 9.50 MeV are shown in Fig. 2.

Microscopic distorted-wave impulse approximation (DWIA) calculations for the $0^+ \rightarrow 1^+$ cross sections were carried out with the code DWBA70[19] using transition amplitudes obtained from a recent shell-model calculation with a new *sd*-shell Hamiltonian,[20] an optical potential[6] determined from ^{40}Ca(p,p) data at 200 MeV which gave a reasonable fit to our ^{28}Si(p,p) data, harmonic-oscillator bound-state wave functions with an oscillator parameter of 1.82 fm, and the unpublished nucleon-nucleon interaction of Love and Franey (LF).[21] The calculated cross sections changed by <10% when we used other available optical potentials or the published LF interaction.[22]

The relative cross section curves (solid lines) from these calculations have been multiplied by normalizing factors to produce the fits to the data which are shown in Fig. 2. These normalization factors are listed in Table I, in which we present the correspondences that we are able to make between the experimentally observed and the calculated 1^+ states of ^{28}Si below 15 MeV. The calculated (p,p') cross sections at a center-of-mass angle of 4° and theoretical[20] $B(M1)$ values for these states are also listed. In the two columns headed "Quenching" are given the normalization factors for (p,p') $(=\sigma_{\text{exp}}/\sigma_{\text{calc}})$ and (e,e') $[=B(M1)_{\text{exp}}/B(M1)_{\text{th}}]$. For the first five $T=1$ levels, $B(M1)$ values are known also from (γ,γ') measurements[23] and they agree with the (e,e') values.

We first discuss the $T=1$, 1^+ states. Their measured (p,p') angular distributions all have nearly the same shape, which is somewhat steeper than the calculated shape. This has been observed also for other nuclei.[5,6] The experimental counterpart of the state calculated at 12.97 MeV was not observed, probably because its predicted cross section is only 10^{-4} of that for the 11.52-MeV level.

The $B(M1)$ and (p,p') quenching factors extracted for the succession of individual states fluc-

TABLE I. Comparison of observed 1^+ levels in ^{28}Si with *sd*-shell model.

E_x (MeV) Expt.	Theory[a]	$\sigma^{\text{th}}_{p,p'}$ (mb/sr)	$B_{\text{th}}(M1)\uparrow$ (μ_0^2)	Quenching (p,p')	Quenching (e,e')[b]
		$T=1$ states			
10.59	10.81	1.40	1.52	0.15	0.22
10.73	10.96[c]	0.009	0.003		
10.90	11.19	0.14	0.54	0.54	1.26
11.45	11.52	1.54	3.06	0.66	1.33
12.33	12.64	1.28	1.39	0.16	0.58
· · ·	12.97	0.00	0.00	· · ·	· · ·
13.35	13.37	0.27	0.008	0.51	· · ·
14.03	14.38	1.34	0.92	0.33	0.49
15.15	14.61	0.62	0.87	0.25	0.21
15.50	15.02	0.36	0.48	0.18	0.46
Overall ($T=1$)				0.33	0.77
		$T=0$ states			
8.33	7.94	0.19	0.008	· · ·	· · ·
9.50	9.40	0.73	0.031	0.29	· · ·
· · ·	10.96	0.01	0.0003	· · ·	· · ·
· · ·	11.71	0.03	0.002	· · ·	· · ·
· · ·	12.27	0.19	0.008	· · ·	· · ·
· · ·	12.93	0.05	0.002	· · ·	· · ·
· · ·	13.50	0.004	0.0001	· · ·	· · ·
Overall ($T=0$)				0.24	· · ·

[a] Ref. 20.

[b] Refs, 17, 18, and 20.

[c] Calculated to be a $T=0$ state. It appears in the experimental $T=1$ spectrum presumably because of isospin mixing.

tuate significantly from state to state. This variation reflects the inadequacy of the present stage of structure model calculations in dealing with the detailed distribution, among a cluster of states, of the total strength allocated for the cluster as a whole. While the detailed distribution is sensitive to the nuances of the model calculations, the total strength is not. Hence, we focus here on the ratio of the total observed strength to the corresponding total predicted strength. The model calculations predict that the preponderance (> 80%) of the total isovector spin-flip strength is concentrated below 16 MeV excitation energy. The ratio of the observed (p,p') strength in the 10–16-MeV region of excitation to that predicted for $T=1$ states in the same range is 0.33. The difference between this factor 0.33 for (p,p') and the corresponding factor of 0.77 obtained for the ratio of experimental to theoretical $B(M1)$'s reflects the contributions of the orbital part of the $M1$ operator which are missing in the (p,p') process and the larger (positive) exchange-current contributions to the $M1$ operator relative to the Gamow-Teller-like (p,p') operator.

Most of the isoscalar spin-flip strength (> 85%) is predicted by our shell model to lie below 14 MeV. Predictions and observations are compared in Table I. The only states which are predicted to have cross sections measurable in the present experiment are the first, second, and fifth. On the basis of γ-decay systematics,[16] two $T=0$ states are known experimentally, at excitation energies of 8.33 and 9.50 MeV. Only the 9.50-MeV state is clearly excited in our experiment. The 8.33-MeV state has cross sections no greater than one-tenth the cross sections of the 9.50-MeV state. The angular distribution for the 9.50-MeV state is shown at the bottom right-hand part of Fig. 2. It is much flatter than the angular distributions observed for the $T=1$, 1^+ transitions. The DWIA calculations predict this difference between the $T=0$ and $T=1$ data. It can be understood as the consequence of the strong, attractive $V_{\sigma\tau}$ interaction in the $T=1$ channel. The good fit obtained for the angular distribution of the 9.50-MeV state is an indication of the pure isoscalar nature of this state. (A known 2^+ level at 9.48 MeV is unresolved from the 9.50-MeV level. The dotted curve represents the contribution of the 2^+ level. Its shape is that which we measured for a known 2^+ doublet at 7.38–7.42 MeV, while its magnitude has been arbitrarily adjusted.)

As with the $T=1$ states, we compare the strength measured for the $T=0$ state at 9.50 MeV with the aggregate of predicted strength around this region of excitation energy. In practice, this means we exclude from the theoretical sum all of the states above the second. The resulting ratio of experimental to theoretical strength is 0.24. This is quite comparable to 0.33, the ratio found for $T=1$ strength.

In summary, we find that the extent of quenching for the $0^+ \rightarrow 1^+$ isoscalar transition in ^{28}Si is large and comparable to that for the isovector transitions. While the actual magnitude of this quenching is dependent on the details of the calculations that we have used to extract it, the relative amounts of quenching in the two channels should be less sensitive to these details. The comparable quenching in the two channels indicates that the Δ-isobar admixture mechanism alone is not sufficient to explain the quenching. Our result, while not ruling out this mechanism, points to the importance of higher-order configuration mixing as a quenching mechanism.

This work was partly supported by the U. S. National Science Foundation under Grants No. PHY-80-17605 and No. INT-82-63242 and in part by the University of Paris XI.

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