Electroexcitation of 6^- States in ^{32}S

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Inelastic electron scattering is used to identify nine stretched isovector $[T_> \ (T_0 \rightarrow T_0+1)]$ $M6$ transitions in ^{32}S ($T_0=0$) which exhaust $(77\pm17)\%$ of the extreme single-particle-hole-model sum rule. This is the first time that several prominent $T_>$ electromagnetic stretched transitions have been observed in a self-conjugate nucleus and the first time that such a large fraction of the sum rule has been observed. These effects are primarily due to the presence of spectator nucleons in the $2s_{1/2}$ orbit, as substantiated by shell-model calculations.

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During the past decade there has been an intense experimental effort to determine the strength distributions for nuclear magnetic excitations. The high-spin stretched excitations are one class of the above that have received particular attention.[1] The experimental data obtained to date have provided important tests of hadronic effective interactions and reaction processes[1,2] and have motivated a number of nuclear-structure calculations.[3-6] In this Letter, we report new data on the electroexcitation of nine stretched $T_>$ ($T_0 \rightarrow T_0+1$) 6^- states in ^{32}S ($T_0=0$) with roughly comparable strength. The large number of observed fragments in ^{32}S are in contrast to the results of previous experiments on lighter self-conjugate *sd*-shell nuclei, i.e., ^{24}Mg and ^{28}Si,[7] where essentially all of the observable stretched $T_>$ strength was found in a single peak. The difference between the ^{32}S results and the lighter *sd*-shell nuclei suggests that the distribution of isovector stretched strength is strongly dependent on the presence of spectator nucleons beyond the hole orbit of the stretched configuration. Previous ^{32}S(e,e') work[8] investigated states at excitation energies below the region where the 6^- states occur, and an early ^{32}S(p,p') study[9] carried out with inadequate resolution and an insufficient energy range failed to find any 6^- strength. However, a more recent ^{32}S$(p,n)^{32}$Cl experiment[10] identified a large number of possible 6^- states, but was unable to determine the strength with the same accuracy as in the (e,e') reaction.

Pressed, 22-mg/cm^2-thick targets[11] of 99.9% pure Li_2S containing natural sulfur (95% ^{32}S) and natural lithium (92.5% ^{7}Li) were bombarded with electrons from the Sektie Kernfysica, Nationaal Instituut voor Kernfysica en Hoge-Energiefysica (NIKHEF-K) electron linear accelerator.[12] Using the quadrupole-dipole-dipole (QDD) spectrometer, spectra (see Fig. 1) were

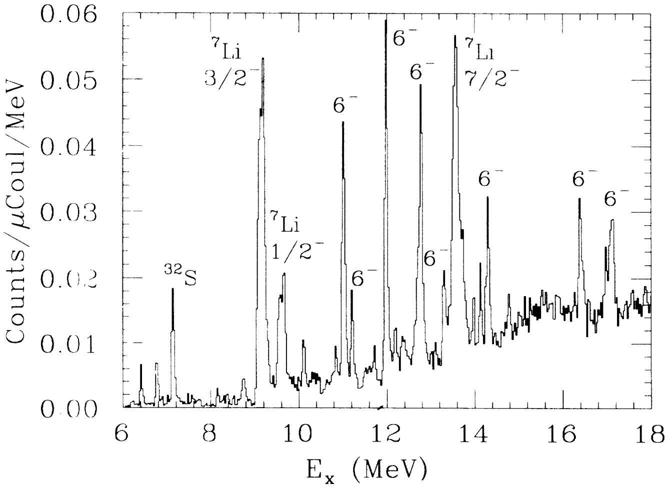

FIG. 1. A sample ^{32}S(e,e') spectrum taken at NIKHEF using a Li_2S target. The scattering angle is $\theta=154°$ and the incident electron energy is $E_0=207$ MeV ($q=2.0$ fm^{-1}).

TABLE I. Excitation energies E_x for the $T_> \, 6^-$ states observed in ^{32}S(e,e') and associated spectroscopic strengths Z_1^2 and errors deduced from the least-squares fit to the data using an average $b=1.80\pm0.04$ fm. The summed strength for the ^{32}S$(p,n)^{32}$Cl reaction (Ref. 10) must be deduced to 0.45 to account for 5^- contamination. The theoretical results are from the large-basis calculations fully described in Ref. 6.

^{32}S(e,e')		^{32}S theory		^{32}S$(p,n)^{32}$Cl	
E_x (MeV)	Z_1^2	E_x (MeV)	Z_1^2	E_x (MeV)	Z_1^2
10.98 ± 0.04	0.135 ± 0.031	11.2	0.055	3.8	0.064
11.17 ± 0.05	0.030 ± 0.012	⋯	⋯	⋯	⋯
11.94 ± 0.04	0.126 ± 0.027	12.4	0.051	4.7	0.071
12.74 ± 0.04	0.121 ± 0.005	12.9	0.306	5.6	0.113
13.26 ± 0.05	0.036 ± 0.010	13.6	0.053	6.3	0.099
13.54 ± 0.05	0.087 ± 0.028	14.1	0.043	6.8	0.028
14.29 ± 0.05	0.058 ± 0.003	14.3	0.049	7.3	0.042
⋯	⋯	15.1	0.063	8.4	0.014
⋯	⋯	15.5	0.046	⋯	⋯
16.43 ± 0.07	0.059 ± 0.006	16.3	0.057	9.2	0.042
17.16 ± 0.08	0.059 ± 0.008	17.2	0.048	9.8	0.050
$\sum(Z_1)^2_{ee}=0.71\pm0.05$		$\sum(Z_1)^2_{\text{th}}=0.77$		$\sum(Z_1)^2_{pn}=0.52$	

taken at five incident electron energies from 151 to 258 MeV at a scattering angle of 154°. To allow discrimination between longitudinal and transverse transitions, three other spectra were taken with similar momentum transfer but different incident energies and scattering angles: one at NIKHEF-K at 258 MeV and 118°, as well as two at the MIT Bates Linear Accelerator Center at 182 MeV and 180° and at 222 MeV and 140°, using the energy-loss spectrometer system (ELSSY).[13]

The ^{32}S $M6$ excitation energies listed in Table I were based on a spectrometer calibration using low-lying states in ^{7}Li and ^{12}C and the strong stretched states at 18.975 MeV in ^{16}O and 14.356 MeV in ^{28}Si. Data analysis used the line-shape fitting program ALLFIT,[14] with an empirical linear background and average peak widths of 100 keV FWHM. The ^{7}Li cross sections from the Li$_2$S target were normalized to previous ^{7}Li data,[15] and the ^{32}S $M6$ form factors shown in Fig. 2 were adjusted accordingly. Distortion effects are accounted for by replacing the momentum transfer q by the effective momentum transfer q_{eff}.[1]

Electron-scattering form factors were calculated with simple harmonic-oscillator (HO) wave functions and least-squares fitted to the data. The sum of the extracted spectroscopic Z coefficients[16] $\sum Z_1^2$ were compared to the extreme single-particle-hole-model[1] (ESPM) isovector strength [with $\sum(Z_1)^2_{\text{ESPM}}=1$] for $(f_{7/2}d_{5/2}^{-1})^{6^-}$ assuming that the $d_{5/2}$ orbital is filled with twelve nucleons. For a least-squares fit allowing the oscillator parameter b to vary independently for each state as shown in Fig. 2, the total Z_1^2 was 75% of the ESPM strength. The use of an average $b=1.80\pm0.04$ fm to fit all states resulted in a total Z_1^2 of 71%. The strengths determined for the individual states using this average b are listed in Table I and compared with the preliminary results from the ^{32}S$(p,n)^{32}$Cl experiment[10] where $b=1.77$ fm was used. The 71% fraction for ^{32}S is in contrast to the well established 30% to 50% fraction (determined in a consistent manner[17]) that has been observed in previously studied p- and sd-shell nuclei.[1] The extracted Z_1^2 is decreased to 60% if meson-exchange-current (MEC) effects are included.[1]

Form factors were also calculated using more realistic Woods-Saxon (WS) wave functions[17] generated from the code DWUCK4,[18] with the potential diffuseness and spin-orbit parameters fixed at $a=0.65$ fm^{-1} and $\lambda=25$, respectively. For a least-squares fit allowing the potential radius parameter r_0 to vary independently for each state as shown in Fig. 2, the total Z_1^2 was 93% of the ESPM strength. The use of an average $r_0=1.20$ fm to fit all states resulted in a total Z_1^2 of 88%. The WS Z coefficients were larger than the HO ones by a factor varying from 1.1 for the lowest states to 1.4 for the highest states. Overall, the observed fraction ranges from 60% to 93% of the ESPM strength, or 77% ± 17%.

A recent large-basis shell-model calculation[5] that gives an excellent description of the stretched $M6$ strength distribution in ^{28}Si has been extended[6] to ^{24}Mg and ^{32}S using the same $(d_{5/2},s_{1/2})^{\alpha-n}d^n_{3/2}f_{7/2}$ $J=6$ basis with $\alpha=A-17$ and $n\leq4$. These calculations predict that ^{24}Mg and ^{28}Si have a strong yrast $T_>$ state carrying about 40% of the total isovector stretched strength, with the remainder spread across many weak states starting several MeV above the yrast state. This is consistent with experiment. The results for ^{32}S, summarized in Table I, predict that the yrast state will not be the strongest state, that several states should be easily visible within a few MeV of each other, and that the sum of the strengths predicted in the 11-17-MeV region is large, about 77% of the extreme single-particle-hole model.

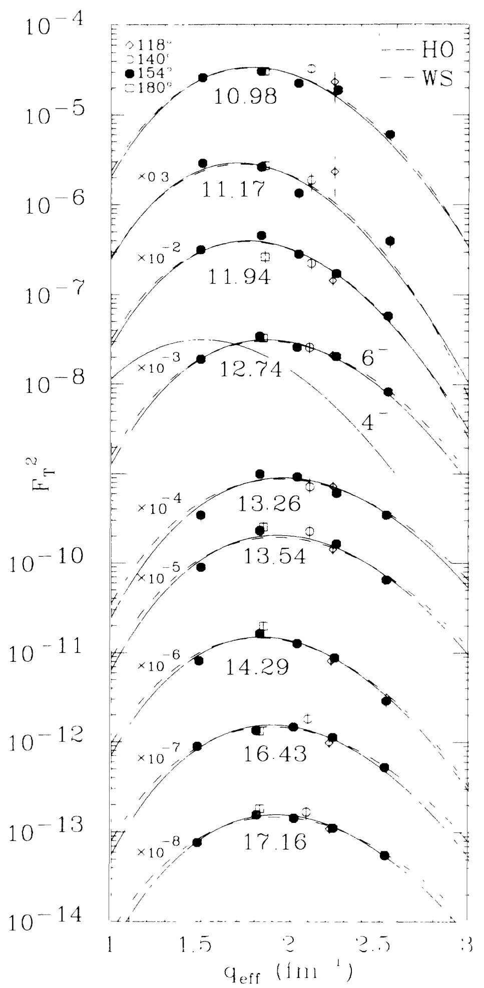

FIG. 2. Form factors as defined in Ref. 1 for the ^{32}S(e,e') 6^- stretched states (with excitation energies in MeV), where the HO b and the WS r_0 were varied independently for each state. A form factor calculated for a 4^- excitation is shown to illustrate the basis for rejecting the 4^- spin assignment.

This is also consistent with the qualitative features of the data. It is the spectator nucleons in the $2s_{1/2}$ orbit that are responsible for the change in the spectral distribution of $T_>$ strength in going from ^{24}Mg and ^{28}Si to ^{32}S. We finally note that a similar change in the distribution of $M1$ strength between ^{28}Si and ^{32}S has been observed.[8] Both the $M1$ and $M6$ excitations are built on $d_{5/2}$-hole states, which can be studied by nucleon pickup reactions. These reactions populate[19] only one strong $d_{5/2}$-hole state in ^{24}Mg and ^{28}Si, but several $d_{5/2}$ states (with about equal strength) in ^{32}S. The latter observations are also consistent with the shell model.

Examination of the $T_>$ stretched strength in other even-even p-, sd-, and fp-shell nuclei indicates that this trend persists. Specifically, one $T_>$ state is observed in ^{12}C, ^{24,26}Mg, ^{28}Si, ^{52}Cr, and ^{54}Fe where the $p_{3/2}$, $d_{5/2}$, and $f_{7/2}$ levels are being filled.[7,20] However, in ^{16}O, ^{40}Ca, and ^{58,60}Ni which contain spectator nucleons beyond the $p_{3/2}$, $d_{5/2}$, and $f_{7/2}$ orbits, respectively, several $T_>$ states appear to be excited.[7,10] The results for self-conjugate p- and sd-shell nuclei are summarized in Fig. 3. The effect is not as pronounced in the ^{16}O and ^{14}C p-shell nuclei. In ^{16}O the observed strength is more concentrated in a single state than in ^{32}S, and in ^{14}C one high-lying $T_>$ state is observed as a broad peak that overlaps with neighboring levels.

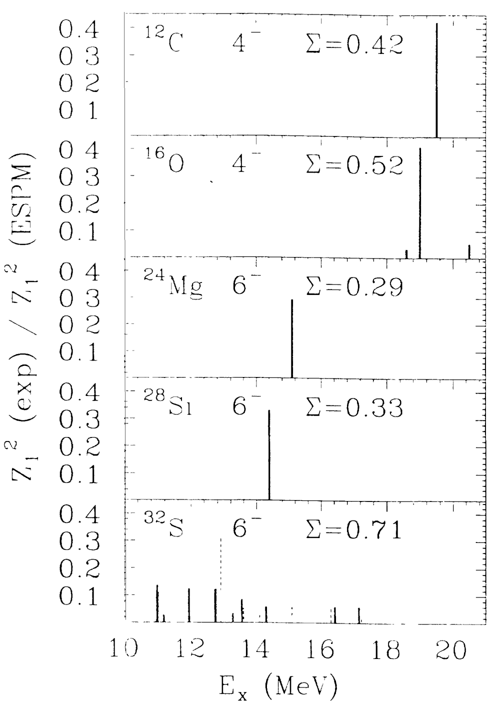

FIG. 3. The fraction of ESPM strength [calculated consistently for all nuclei (Ref. 17)] for the known (Ref. 7) isovector electromagnetic stretched transitions to 4^- and 6^- states in even-even self-conjugate nuclei. The strength shown for ^{12}C and ^{16}O is that which would be observed in the absence of isospin mixing. The dashed lines for ^{32}S represent the shell-model predictions.

In contrast, the $T_<$ $(T_0 \rightarrow T_0)$ strength is observed to be fragmented in all $N \neq Z$ nuclei discussed here, even when spectator nucleons are absent. This suggests that the mechanism responsible for the $T_<$ fragmentation is quite different than that responsible for the $T_>$. The mechanism is probably due to the increased number of particle-hole configurations that can be constructed when the hole orbital has unequal numbers of protons and neutrons.

In conclusion, the observable stretched $M6$ $T_>$ strength in ^{32}S is spread among several levels of comparable magnitude, rather than isolated in a single level as in lighter sd-shell nuclei. Results from large-basis shell-model calculations in ^{28}Si and ^{32}S support these observations. The new ^{32}S(e,e') data reported here provide clear evidence of the important role of spectator nucleons beyond the hole orbit in the fragmentation of stretched magnetic strength. This is corroborated by data on the distribution of $T_>$ stretched strength for other nuclei up to the fp shell. The systematics of $M6$ transitions in sd-shell nuclei are particularly profitable to study because they are observed in a large number of self-conjugate nuclei and large-basis shell-model calculations can be performed for these systems. Examination of ^{36}Ar would be a good additional test of the role of spectator nucleons.

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