PREDICTION OF A NEW HIGH-SPIN MODE OF TRANSVERSE EXCITATION IN ELECTRON SCATTERING FROM NUCLEI

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Recent shell-model calculations predict strong concentrations of transverse E4 excitation strength in nuclei near the middle of the sd shell. These excitations are examples of a mode which has its microscopic origin in a unique pair of shell-model orbitals, in the case of the sd shell the $0d_{5/2}$–$0d_{3/2}$ orbitals. The excitation strength predicted to occur near 7 MeV in ^{26}Mg appears to be observed in recent electron scattering measurements.

1. Introduction. Modes of nuclear excitation which are mediated through a unique pair of shell-model orbitals are particularly interesting because of their freedom from the ambiguities which arise from interference between competing one-body transition paths. Such excitations yield direct insight into the many-nucleon structure of model wave functions and the global renormalization properties of the fundamental nuclear operators.

One example of such a unique-orbital excitation, which has been extensively studied, is the transverse magnetic mode, in which the total angular momentum transfer, ΔJ, has the maximum possible value for a given set of active single-particle orbitals. We will refer to this as the MJ_{max} mode. In this mode, each member of the unique pair of orbitals has the maximum j-value, j_{max}, for its major shell. Because these transitions are characterized by high angular momentum they stand out in spectra measured at large momentum transfers.

There are two classes of these MJ_{max} excitations, one in which the two orbitals belong to the same major shell and the other in which the final j_{max} belongs to a mostly unfilled major shell lying above the (mostly filled) major shell to which the initial orbital belongs. Examples of the former are the "stretched" states observed in (p, n) reactions, such as the M7 in ^{48}Ca(p, n) [1], and the high-momentum transverse elastic electron scattering on odd–even nuclei, such as the M5 for ^{27}Al [2] and the M7 for ^{51}V [3]. Examples of the latter are the "stretched" states seen in inelastic electron and hadron scattering [4], such as the M4 in ^{16}O [5], the M6 in ^{28}Si [6], the M8 in ^{48}Ca [7] and ^{54}Fe [8], and the M14 in ^{208}Pb [9].

There is an analogous unique-orbital mode for transverse electric excitations which we will refer to as the EJ_{max} mode. This mode has received little theoretical or experimental attention. As we will see below, it is characterized by values of j_{max} and $j_{max}-1$ for the unique pair of orbitals. Of course, the formal existence of such a mode of excitation begs the question of whether it is manifested experimentally in concentrations of strength which are susceptible to measurement. Some evidence for the existence of this EJ_{max} mode can be found in electron scattering to the 2^+ $T=1$ state at 16.11 MeV in ^{12}C [10], which corresponds to the unique transition $0p_{3/2}\to 0p_{1/2}$, and to the 12^+ state at 6.10 MeV in ^{208}Pb [11], which

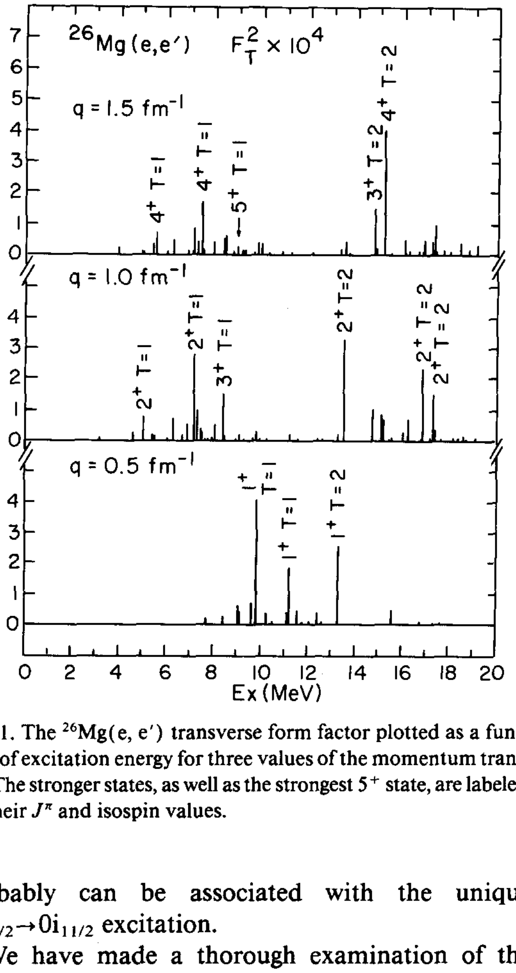

Fig. 1. The ^{26}Mg(e, e′) transverse form factor plotted as a function of excitation energy for three values of the momentum transfer. The stronger states, as well as the strongest 5^+ state, are labeled by their J^π and isospin values.

probably can be associated with the unique $0i_{13/2} \to 0i_{11/2}$ excitation.

We have made a thorough examination of the strength functions of all modes of longitudinal and transverse excitations which are predicted by the complete space sd-shell model wave functions of Wildenthal [12]. For nuclei near the center of the shell the spectra of transverse excitation strength shows striking peaks at high momentum transfers in the range of excitation energy between 7 and 15 MeV. Analysis of these peaks shows them to result from $0d_{5/2} \to 0d_{3/2}$ E4 transitions which exhaust significant fractions of the total strength available for this mode of excitation. The calculated transverse excitation functions for ^{26}Mg for three values of the momentum transfer are shown in fig. 1. A strong state near 7.3 MeV in excitation energy, which appears to correspond to our prediction at this energy, has recently been discovered in the analysis of electron scattering data [13].

For these strong transverse E4 states predicted by the shell model we find that the magnetization-current (MC) part of the TE operator makes the dominant contribution. The convection-current contributions, which at low-momentum transfer can be related to the longitudinal form factor via the continuity equation (see section IV.E of ref. [14]), are very small in the higher momentum transfer region in which the MC contribution peaks. The reduced single-particle TE(MC) matrix element used in the plane-wave impulse approximation obeys the symmetry relation [14]

$$\langle j \| \mathrm{TE(MC)} \| j' \rangle = (-1)^{j-j'+1} \langle j' \| \mathrm{TE(MC)} \| j \rangle \, .$$

As a consequence, the diagonal matrix elements ($j=j'$) of the TE(MC) operator vanish. Hence, the EJ_{max} form factors are dominated by transitions of the type $j_> = l+\frac{1}{2} \to j_< = l-\frac{1}{2}$, with $J_{max} = j_> + j_< = 2l_{max}$, where l_{max} is the largest value of the single-particle orbital angular momentum l within a given major shell.

We note that M1 excitations also have a large $j_> \to j_<$ component. However, the M1 mode is more complicated since $j_> \to j_>$ transitions are also allowed. For closed shell configurations in nuclei such as ^{208}Pb, these $j_> \to j_>$ components are completely blocked, but they enter with some strength from the non-closed shell components of the ground-state wave function. In contrast, these $j_> \to j_>$ components are never present for the EJ_{max} mode because of the selection rules associated with the operator.

The strengths of these EJ_{max} transitions are maximized by having the $j_>$ orbit filled and the $j_<$ orbit empty. In the sd shell this is realized in ^{28}Si. The strongest E4 we predict from the wave functions of ref. [12] is for a $T=1$ state in ^{28}Si at 11.68 MeV excitation. The E4 form factor for this state peaks at $q = 1.65$ fm^{-1} (using harmonic-oscillator radial wave functions with $\hbar\omega = 12.4$ MeV) and has a peak value of 0.7×10^{-4} (in the units defined in ref. [14]). This state exhausts about 60% of the total E4 (MC) strength in this nucleus. Due to ground-state configuration mixing in the full sd-shell wave function, the total strength predicted is about a factor of two smaller than that obtained with the zeroth-order, $(0d_{5/2})^{12}$, ground-state configuration.

This 4^+ $T=1$ state in ^{28}Si is the analogue of the 4^+ state in ^{28}Al which lies experimentally at 2.27 MeV excitation [15]. Thus, the experimental state should be at about 11.59 MeV excitation in ^{28}Si (i.e., 2.27 MeV above the known lowest $T=1$ state at 9.32 MeV). A state at this energy is seen in the 160° (e, e′) spectrum of ref. [6], but the momentum transfer for this spectrum ($q=1.9$ fm^{-1}) is not optimum for E4. A state at 11.59 MeV has also been observed in inelastic pion scattering and assigned as a 6^- $T=0$ state [16] (a 6^- $T=0$ state should be very weak in the electron scattering since isoscalar magnetic excitations are intrinsically a factor of $[(g_p-g_n)/(g_p+g_n)]^2=29$ weaker than isovector transitions). Indeed, both of these states may be present at 11.59 MeV.

The E4 transitions are also strong in ^{26}Mg, see fig. 1. Since the ground state of ^{26}Mg has $T=1$, the $\Delta T=1$ excitations are divided between the final states with $T=1$ and $T=2$. We predict the strongest states to lie at excitation energies of 7.41 MeV ($T=1$) and 15.14 MeV ($T=2$) with peak values of 0.18×10^{-4} and 0.42×10^{-4}, respectively. These states exhaust about 40% ($T=1$) and 70% ($T=2$) of the total calculated E4 strength. These total strengths amount to 50% of the total strength obtained with the zeroth-order $(0d_{5/2})^{10}$ ground-state configuration. The isospin splitting has brought the strength in the $T=1$ state down into a region of the spectrum in which any M4 and M6 excitations should be weak.

The experimental identification of the EJ_{max} excitation mode is not model independent. Using harmonic-oscillator radial wave functions, the E4 form factors are calculated to have exactly the same shape for the sd-shell configurations as M5 form factors. Thus, the shape cannot be used as a means of discriminating between these two modes. However, for the zeroth-order configurations $[(0d_{5/2})^{12}$ for ^{28}Si and $(0d_{5/2})^{10}$ for $^{26}Mg]$ M5 excitations are not allowed and even with the configuration mixed wave functions of ref. [12] the calculated M5 strength is negligible compared to the E4 strength. (The strongest predicted M5 state for ^{26}Mg is labeled in fig. 1.)

The strongest competing transitions likely to be observed experimentally in the transverse spectrum of ^{26}Mg arise from the cross-shell M4 and M6 excitations. The lowest and strongest 6^- (M6) $T=1$ state in ^{28}Si has been identified at 14.36 MeV in (e, e′) [6]. Based on a pure $0d_{5/2}\rightarrow0f_{7/2}$ transition we calculate the M4 form factor to peak at $q=1.27$ fm^{-1} and the M6 form factor to peak at $q=1.82$ fm^{-1}. Thus, from the position of the maximum one may qualitatively discriminate these from the E4 excitations which peak at $q=1.65$ fm^{-1}.

Of course, an E4 state can be discriminated from M4, M5 and M6 states by the fact that the E4 can contain a longitudinal (C4) component, whereas for the ML transitions the longitudinal components must vanish. For the state at 11.68 MeV in ^{28}Si, we calculate a longitudinal form factor which peaks at $q=1.5$ fm^{-1} with a value of 0.17×10^{-3} (again in units of ref. [14]). However, there is probably some uncertainty in this calculated value since it is relatively weak compared to the strong C4 transitions for 4^+ states at low excitation [17].

It is interesting to note that the state at 7.41 MeV in ^{26}Mg is the sixth 4^+ state predicted in the shell model spectrum. Many of the lower states have been studied previously in (e, e′) experiments, being observed through their strong C4 components [18]. the calculated C4 form factor for the 7.41 MeV state has a peak value of 0.8×10^{-4}; however, again we note that because of its relatively small magnitude this value is somewhat uncertain.

Several additional experiments are suggested by our analysis. This EJ_{max} mode may be selectively excited by other probes such as pions and protons. However, we note that these normal-parity EJ-type transitions are relatively weak in (p, n) reactions with E_p in the range of 100–200 MeV [19]. It would be interesting to look for stretched EJ transitions in other nuclei. The E4 in ^{28}Si and the E6 in nuclei around the ^{48}Ca and ^{56}Ni closed shells would be good candidates.

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