Concentrated Particle-Hole Strength Observed in $0\hbar\omega$ Stretched-State Excitations

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The wide-angle spectra of the 134-MeV (p,n) reaction on ^{48}Ca, ^{54}Fe, ^{88}Sr, and ^{208}Pb are each dominated by the excitation of a single state at low excitation energy. These excitations correspond to the "$0\hbar\omega$" stretched states and are seen to be fragmented much less than "$1\hbar\omega$" stretched states in medium- and heavy-mass nuclei. The normalization factors required for comparison with distorted-wave impulse-approximation calculations are > 0.50 and indicate that these are the purest particle-hole states known in these nuclei.

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There has been considerable interest in the detailed study of particle-hole excitations in nuclei to test both nuclear structure and reaction-mechanism models. Particle-hole states in nuclei are relatively simple excitations which, one hopes, should be amenable to theoretical description. Two popular examples of such excitations which have been studied recently are Gamow-Teller states and "$1\hbar\omega$" stretched states. In this Letter we present another example of a particle-hole excitation which is unique in that the strength is more highly concentrated into a single state, even in medium- and heavy-mass nulcei. These excitations we refer to as "$0\hbar\omega$" stretched states.

A stretched particle-hole configuration is one where the particle and the hole are both in stretched subshells $(j = l + \frac{1}{2})$, and are coupled to the maximum possible angular momentum $j = j_p + j_h$. Usually, one is considering the *maximum* stretched state involving the particle and hole orbitals of highest angular momentum in their respective shells. Most theoretical and experimental work on the excitation of stretched states involves major configurations with the particle excited into the next major shell above the hole. Such excitations must have odd parity and are referred to as "$1\hbar\omega$" stretched states. The excitation of these states has been studied in inelastic electron, proton, and pion scattering,[1,2] in the (p,n) reaction,[3] and in nucleon-transfer reactions.[4] For nuclei with a neutron excess extending up into the next orbital above the filled proton orbitals, a maximum stretched state may be formed in a charge-exchange reaction creating a proton particle and neutron hole in the same orbital. Because these states involve particle and hole orbitals in the *same* major shell (in fact the same orbital), they are referred to as "$0\hbar\omega$" stretched states. When the excess neutron orbital is the first orbital of a new oscillator shell, it is the orbital of highest angular momentum in the nucleus; the stretched state formed from a particle-hole configuration in that orbital will have a large J value, and will form a state with a unique value of J within $2\hbar\omega$ of excitation. This state will be excited strongly at large momentum transfers predominantly by the (isovector) tensor term of the effective nucleon-nucleon $(N\text{-}N)$ interaction (just as for $1\hbar\omega$ isovector stretched states). Because a $0\hbar\omega$ stretched state is formed as a proton-particle, neutron-hole state in a target with a neutron excess, such states can be excited in charge-exchange reactions, but not in inelastic scattering. Watson *et al.*[5] earlier reported the excitation of the $0\hbar\omega$ stretched state in the reaction ^{48}Ca$(p,n)^{48}$Sc. This Letter reports the excitation of $0\hbar\omega$ stretched states in other medium- and heavy-mass nuclei and shows that these states are the purest particle-hole states known in these nuclei.

A $0\hbar\omega$ excitation involves a particle-hole excitation in a subshell which is often the "valence" subshell of the target. Thus, the $0\hbar\omega$ particle-hole state involves a hole and a particle *both* at the Fermi level in the target; in contrast, a $1\hbar\omega$ state necessarily involves exciting the particle into the next major shell. This particle state is thus considerably above the Fermi surface and is typically highly fragmented, especially in medium- and heavy-mass nuclei.[1,2] Experimentally, highly fragmented strength is difficult to identify unambiguously and the total strength extracted is unreliable. Theoretically, if the strength is fragmented, the simple shell model does not apply and higher-order corrections are required for structure calculations.

Examples of strongly excited $0\hbar\omega$ stretched states in medium- and heavy-mass nuclei are shown in the 134-MeV (p,n) spectra of Fig. 1. The measurements were performed with the beam-swinger neutron time-of-flight facility[6] at the Indiana University Cyclotron Facility. The neutrons were detected in large-volume, mean-timed plastic scintillation detectors[7] at flight paths of 38 to 134 m. Overall observed timing resolutions of 0.7 to 1.5 nsec yielded overall energy resolutions of 330 to 800 keV. The absolute magnitudes of the cross sections were obtained from the known geometrical factors, measured target thickness and beam integration, and calculated neutron detector efficiencies. The overall uncertainty was determined to be $\lesssim \pm 15\%$ by comparison of (p,n) and (p,p') analog transitions.[8] The experimental arrangement and technique were described in detail previously.[9]

The wide-angle spectra of Fig. 1 correspond to large momentum transfers in these reactions and are all characteristically similar. An (apparently) single peak is strongly excited at relatively low excitation energy in each spectrum. Some weakly excited strength is seen near this peak as well as the nuclear continuum at higher excitation energies. For the states observed in ^{48}Sc, ^{54}Co, and ^{88}Y, the excitation energies (viz. 1.10, 0.20, and 1.48 MeV) agree with the known[10] locations of a 7^+, a 7^+, and a 9^+ state, respectively. These states are thus plausibly the $(\pi f_{7/2}, \nu f_{7/2}^{-1})$ $(\pi f_{7/2}, \nu f_{7/2}^{-1})$, and $(\pi g_{9/2}, \nu g_{9/2}^{-1})$ $0\hbar\omega$ stretched states in these nuclei. The $0\hbar\omega$ state at 3.4 MeV in ^{208}Bi would be a 13^+, $(i_{13/2}, i_{13/2}^{-1})$ level. No 13^+ level has been identified previously in this nucleus.

Experimental angular distributions are shown in Fig. 2, where they are compared with distorted-wave impulse-approximation (DWIA) calculations which assume that the states are each simply the appropriate $0\hbar\omega$ stretched-state particle-hole configuration. The calculations were performed with the code DWBA70,[11] with the global optical-model parameters of Schwandt *et al.*,[12] and the *N-N* effective interaction of Love and Franey at 140 MeV.[13] Harmonic-oscillator wave functions were assumed. The normalizations required to make the calculations agree in magnitude with the data vary from 0.54 to 0.96, as indicated. The experimental and theoretical shapes are in generally good agreement.

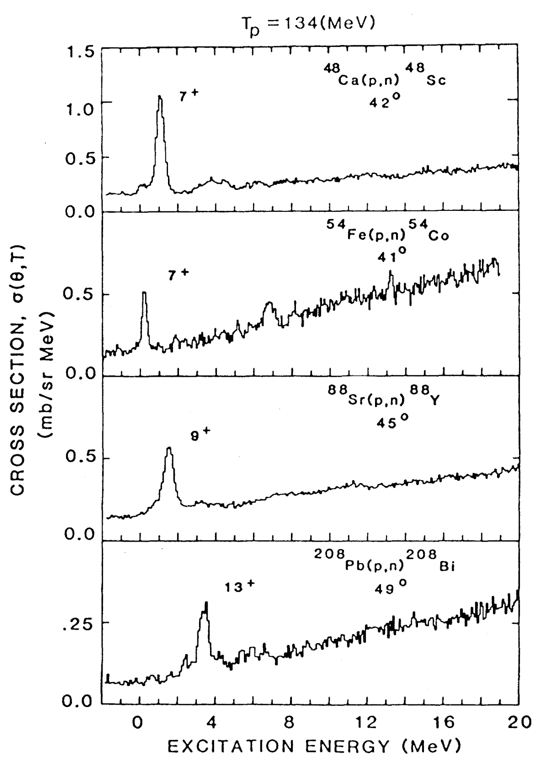

FIG. 1. Excitation-energy spectra from the (p,n) reaction at 134 MeV on some medium- and heavy-mass nuclei.

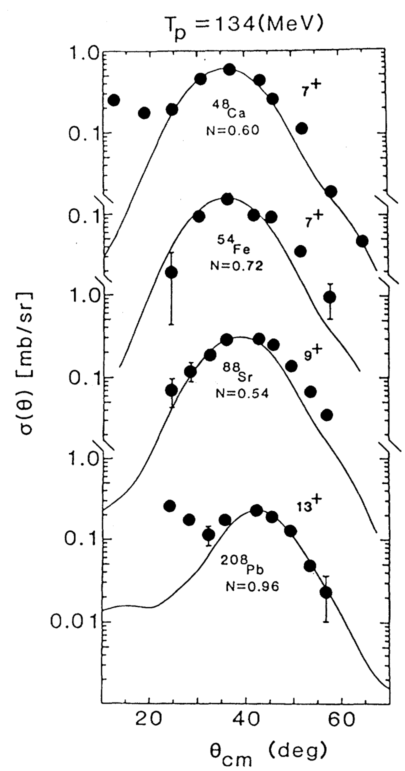

FIG. 2. Angular distributions for the excitation of "$0\hbar\omega$" stretched states in some medium- and heavy-mass nuclei with the (p,n) reaction at 134 MeV. The solid curves represent DWIA calculations with the indicated normalizations (see text).

The excess strength at small angles in the ^{48}Ca and ^{208}Pb angular distributions is from unresolved states with low J values. For the case of ^{48}Ca$(p,n)^{48}$Sc, this strength is due to an unresolved 2^+ state at $E_x = 1.14$ MeV (as discussed in more detail elsewhere[14]). For the ^{208}Pb$(p,n)^{208}$Bi case, specific J^π assignments in this excitation-energy region are lacking; however, the level density near the observed high-spin state makes it likely that some other state(s) will be observed at smaller angles. These states of low spin should not contribute significantly at wider angles. Note also that the normalization factors are uncertain by the combined experimental and theoretical uncertainties. The important point here is that these normalization factors are significantly larger than those obtained for similar analyses of "$1\hbar\omega$" stretched states.

It is important to note that the state which could most easily be confused with the $0\hbar\omega$ stretched state is the next lower-spin state of the same particle-hole band; however, this state will be excited only weakly in these reactions. In the reaction ^{48}Ca$(p,n)^{48}$Sc, for example, the transition to the 6^+ state would be expected to have (essentially) the same angular distribution ($\Delta l = 6$) as that to the 7^+ stretched state; however, as pointed out by Petrovich and Love[15] and also by Picklesimer and Walker,[16] transitions dominated by the tensor term of the N-N effective interaction will excite normal-parity states only via exchange processes, which are expected to be weak. This prediction is verified, in fact, by the reaction ^{48}Ca$(p,n)^{48}$Sc, in which the 6^+ state is known to be the ground state, and is well resolved from the 7^+ state at $E_x = 1.1$ MeV. Experimentally, we see the 6^+ state to be excited with only $\sim 7\%$ of the strength of the 7^+ state, in good agreement with DWIA calculations (which include exchange). Thus, because all the states of these particle-hole bands have positive parity and must involve even values of Δl, the $0\hbar\omega$ transitions in general need only be identified as having an angular distribution which corresponds to $\Delta L = 2l_{\text{orbital}}$ and not $\Delta L = 2l_{\text{orbital}} - 2$.

This analysis seems reliable for the three lighter targets; however, the ^{208}Pb result is less certain. The 13^+, $(i_{13/2}, i_{13/2}^{-1})$ $0\hbar\omega$ excitation requires $\Delta L = 12$. The peak of the DWIA angular distribution shifts by only $\sim 2°$ for each unit of ΔL for this reaction and the location of the peak is uncertain by at least this amount because of uncertainties in the geometrical parameters of the calculations. Hence, although we would not expect to excite strongly a 12^+ state (because it is of natural parity), the observed peak may include an unresolved 11^+ state with $\Delta L = 10$ which is not sufficiently different in the shape of its angular distribution. A state was reported[10] with a tentative 11^+ assignment at $E_x = 3.51$ MeV in ^{208}Bi, which would not be resolved in this experiment. Clearly, it is important to obtain better resolution, perhaps both in (p,n) and in $(^3\text{He},t)$ measurements, in order to identify states in ^{208}Bi in this excitation-energy region, both because ^{208}Pb, which is believed to be a relatively good shell-model nucleus, provides an important test case and because we see that an abnormally large (0.96) normalization factor is obtained for this reaction (on the assumption that the peak is only a 13^+ state).

It is significant that all the normalization factors indicated in Fig. 2 are larger than those observed for $1\hbar\omega$ stretched-state excitations; for example, the normalizations required for the (e,e') and/or (p,p') excitations of the 4^- isovector stretched state in ^{16}O and the 6^- isovector stretched state in ^{28}Si are between 0.25 and 0.40.[1,2,4] Note that our 134-MeV (p,n) studies of the analogs of these two $1\hbar\omega$ stretched states yield normalization factors similar to the (e,e') and (p,p') studies.[1,3] Since both the $0\hbar\omega$ and $1\hbar\omega$ stretched-state excitations are dominated by the tensor term of the N-N effective interactions, they are probably both subject to the same deficiencies in the assumed reaction mechanisms. Hence, the large normalization factors required for the $0\hbar\omega$ excitations indicate that the deficiencies in the assumed nuclear structure, viz. the effects of core polarization and configuration mixing, are less severe for the $0\hbar\omega$ stretched states than for the $1\hbar\omega$ stretched states. Again, this likely follows because the $0\hbar\omega$ states are closer to the Fermi surface where the simple shell model is more valid.

For ^{48}Ca, the fractional occupancy of the $f_{7/2}$ neutron orbital can be estimated from experimental neutron-pickup spectroscopic factors[17] to be $\sim 85\%$; consequently, the DWIA normalization factor of 0.60 for the $0^\pm$ to 7^+ transition in the reaction ^{48}Ca$(p,n)^{48}$Sc should be increased to ~ 0.71 $[= 0.60(1/0.85)]$. Brown[18] performed a shell-model calculation for states in ^{54}Co, in a $1f$-$2p$ shell basis including a certain (limited) class of 2p-2h excitations. This calculation indicates that the 7^+"$0\hbar\omega$" strength expected for this reaction would be reduced by about 10% from the simple shell-model expectation. The normalization required for this case would then be increased to $0.72/0.90 = 0.80$. Thus, we see that there remains only $\sim 20\%$–30% "missing" strength for these two transitions. We expect that the corresponding first-order corrections for the reaction ^{88}Sr$(p,n)^{88}$Y(9^+)

would be similar, but that the reaction $^{208}Pb(p,n)^{208}Bi(13^+)$ may involve less core polarization. [This *may* explain in part, the higher normalization factor observed for the $^{28}Pb \rightarrow {}^{208}Bi(13^+)$ case.] The remaining $\sim 25\%$ of the strength may be accounted for by other effects such as meson-exchange currents, isobar currents, and second-order core polarizations. Note that these effects do not necessarily all act to *remove* strength and will vary in magnitude from nucleus to nucleus.

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