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GAMOW-TELLER STRENGTH IN THE β^+ DECAY OF ^{37}Ca

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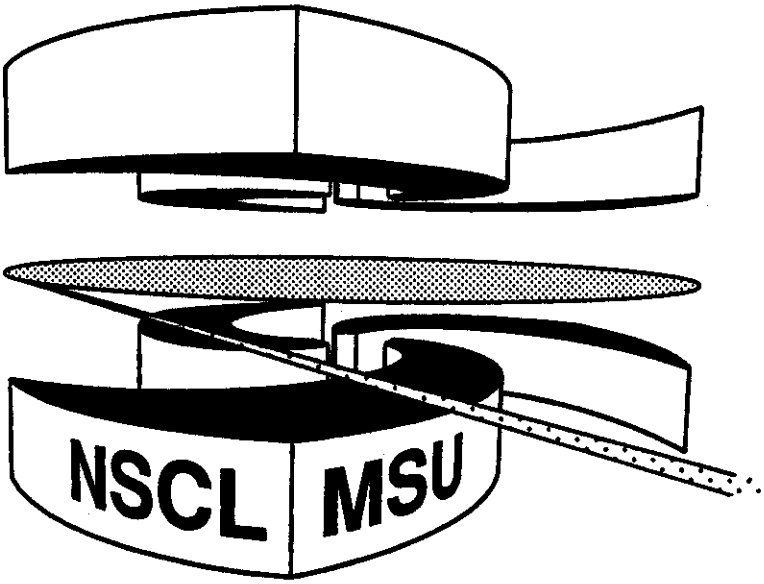

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Abstract: Calculations are presented for the Gamow-Teller strength distribution in the β^+ decay of ^{37}Ca and compared to results extracted from recent data. The distribution is shown to be sensitive to the Hamiltonian, and comparison with experiment indicates a need for further modification to Wildenthal's 0s1d shell interaction. It also indicates that the quenching of the Gamow-Teller operator in the upper part of the 0s1d shell is similar to that deduced from previous analyses.

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In a recent letter,[1] it was proposed that the analysis of the ^{37}Ca β^+ decay data called into question the extent to which the weak axial-vector current is renormalized in nuclei. This result was based on the fact that the Gamow-Teller decay strength extracted from the new data was about equal to that obtained from a shell-model calculation with the free-nucleon value for g_A. It was also claimed that this result cast some doubt on previous conclusions that the experimental Gamow-Teller strength for nuclei with A=17-39 was systematically only about 60% of that expected from 1s0d shell-model calculations.[2,3] This reduction is referred to as a "quenching" of the experimental strength relative to the model. In this letter, I will show that the quenching extracted from the ^{37}Ca β^+ decay data is very model dependent. In particular, I will show that the shape of the Gamow-Teller strength distribution is sensitive to the Hamiltonian. Also I will comment on the comparison to the ^{37}Cl(p,n) data.

In Fig. 1 the B(GT$^+$) strength extracted from the ^{37}Ca β^+ decay and from ^{37}Cl(p,n) data (dashed lines) is compared with 1s0d shell-model calculations based upon four different effective Hamiltonians (solid lines). In order to emphasize the qualitative aspects of the comparison, what is shown is the B(GT$^+$) strength vs excitation energy averaged over a Gaussian distributions with a FWHM of 2 MeV. The area under each curve is equal to the total B(GT$^+$) strength. The experimental data up to about 8 MeV (the vertical dashed line in Fig. 1) is from the ^{37}Ca β^+ decay (Table 1 of Ref 4). Above 8 MeV the B(GT) for states at 9.65 MeV and 11.5 MeV inferred from the (p,n) reaction on the mirror nucleus ^{37}Cl (Table I of Ref 5) is also included.

Two curves are given for each theoretical calculation in Fig. 1. The upper curves are based upon the free-nucleon value of $g_A = 1.251$ and the areas under all these curves is equal to the sum-rule value $\mathrm{B(GT^+)} - \mathrm{B(GT^-)} = 3g_A^2 \mid N_i - Z_i \mid = 14.1$, since B(GT$^-$)=0 for ^{37}Ca in the 1s0d model space. These results will be referred to as the "free-nucleon" calculations. The lower curves are based upon the state and mass dependent effective Gamow-Teller operator of Ref 2. For A=37 this effective operator is within a few percent the same as using a value of $g_A = 0.90$ and the areas under all of the lower curves are about 7.3. These results will be referred to as the "quenched" calculations. A different effective Hamiltonian was used for each of the four comparisons made in Fig. 1. In order to understand the interpretation of the ^{37}Ca decay data, I will summarize the historical background of these Hamiltonians.

The calculation in bottom-left is based upon a microscopic G matrix interaction plus core-polarization corrections (The column labeled 12.5p in Table 1 of Ref 6). The calculation in the bottom-right is based upon the Chung-Wildenthal (CW) "hole" Hamiltonian.[7] The CW Hamiltonian was obtained from a least-squares fit of binding-energy data for nuclei in the A=32-39 region with the least well determined linear combinations of two-body matrix elements being kept at the 12.5p values. In both cases the single-hole energies are chosen to give excitation energies of 2.50 MeV ($1s_{1/2}$) and 6.12 MeV ($0d_{5/2}$) relative to the $0d_{3/2}$ ground state of A=39.

The calculation shown at the top-left is based upon Wildenthal's (W) Hamiltonian.[3] The W Hamiltonian started with the Chung-Wildenthal "particle" (A=17-24) and "hole" (A=32-39) Hamiltonians and made further adjustments so that 447 binding-energy data across the entire 1s0d shell (A=17-39) were reproduced with an rms deviation of a 185 keV.[3,8] 47 linear combinations of the 66 Hamiltonian parameters were relatively well determined by these data.[3,8] One additional feature of this interaction was the introduction of a smooth mass dependence to the two-body matrix elements close to that expected from G matrix interactions..[3,8] The goal and achievement was to obtain a universal one- and two-body Hamiltonian for the entire 1s0d shell which would reproduce experimental data for binding energies, spectroscopic factors, electromagnetic transitions, beta decay and electron scattering form factors.[3] With the W Hamiltonian, the A=39 single-hole states come at 2.73 MeV ($1s_{1/2}$) and 7.42 MeV ($0d_{5/2}$). The $0d_{5/2}$ single-hole energy is significantly higher for the W Hamiltonian than for the CW Hamiltonian. Neither Hamiltonian was constrained to reproduce a specific value for the energy of the A=39 $0d_{5/2}$ hole state, however, it turns out that the energy obtained with the W Hamiltonian is in better agreement with the centroid of the strength observed in one-nucleon pickup from ^{40}Ca.[9] The spectrum labeled WM on the top-right was obtained from the W interaction interaction but with the single-particle energies adjusted to give the same single-hole energies as CW.

Now I discuss the implications of these comparisons. The claim of "no quenching" by Adelberger et al.,[1] is based upon the fact that the areas under the experimental curve and the free-nucleon W calculation (top-left part of Fig. 1) below 8 MeV are about equal. However, it is apparent that only a small part (20%) of the theoretical strength lies below 8 MeV and that the comparison is thus very sensitive to what one assumes for the position of the remaining strength. If one takes the ^{37}Cl(p,n) data as an indication of the shape of the remaining strength it is clear that the total data are much closer to the 12.5p or CW calculations than to the W calculation. Then the interpretation of the data below 8 MeV from the beta decay is that it is consistent with the effective (quenched) Gamow-Teller operator.

Furthermore, it is apparent that the absolute strength obtained from the (p,n) data above 8 MeV is about a factor of two smaller than the quenched calculation. One aspect of the non-proportionality between GT strength extracted from beta decay, $B(GT)_\beta$ and (p,n) experiments, $B(GT)_{pn}$, has previously been noted.[10] In particular, the ratio $B(GT)_{pn}/B(GT)_\beta$ for transitions between "jackknife" configurations ($0p_{1/2} \rightarrow 0p_{1/2}$ and $0d_{3/2} \rightarrow 0d_{3/2}$, in particular) was found to be systematically larger than that between "spin-flip" transitions ($0d_{3/2} \rightarrow 0d_{5/2}$ in this case). The implication of this is that if one calibrates the (p,n) reaction to low-lying transitions with a jackknife structure, the strength extracted for the high-lying spin-flip transitions is too small.[11] A recalibration of the old ^{37}Cl(p,n) data and new higher-resolution data would be important for testing this hypothesis. The proportionality between Gamow-Teller strength extracted from (p,n) reactions and beta decay must eventually break down for transitions which are very weak (a few percent or less) relative to the sum rule value (transitions to the lowest few A=37, T=1/2 levels in this case). There are, of course, additional experimental problems and uncertainties in subtracting the Fermi strength in transitions to analog states (the 5.05 MeV final state in this case).

What one learns from these experiments is that the older Hamiltonians used for the upper 1s0d shell (12.5p and CW) are in better agreement with the GT distribution than the universal W Hamiltonian. A similar conclusion has been reached previously on the basis of the Ar β^+ decay data.[12] Comparison of W and WM indicates that the difference is partly but not entirely related to the position of the $0d_{5/2}$ single-hole state. The failure of the W interaction to give the correct position and shape of the GT distribution in the upper 1s0d shell may imply that it is not possible to describe all binding energy data in the 1s0d shell with a universal smoothly mass-dependent Hamiltonian. However, the CW and W Hamiltonians were determined predominantly from experimental binding energies of low-lying states (up to about 5 MeV in excitation), and consideration of the higher GT strength may be able to better determine some repulsive components of the Hamiltonian to which the low-lying data are not very sensitive.

The problem with the position of the GT strength with the W Hamiltonian is primarily in the upper part of the 1s0d shell; GT strength distributions observed in (p,n) reactions for nuclei in the lower and middle parts of the 1s0d shell (A=18-32) are in overall good agreement with the W Hamiltonian [Ref 3 and references therein]. In fact, for A=18 and 19 there are several cases where most of the GT strength resides in low-lying levels which are directly populated in beta decay[2] and whose energies were integral in determining the W Hamiltonian. Thus, the previous conclusions concerning the quenching of GT strength,[2] which are based primarily on β decay data in the lower and middle parts of the 1s0d shell, are still valid. In addition, I point out that the quenching obtained from the ^{39}Ca β^+ decay[2] and the ^{39}K(p,n) data[10] is completely independent of the 1s0d Hamiltonian.

Quenching of GT strength is clearly a model dependent concept. In the cases discussed above it the relationship between the GT strength observed in the beta decay to discrete low-lying states (when the model is good enough to make a state by state assignment) or to the GT strength summed over a many final states (when the model is not good enough to make a state by state assignment) compared to that predicted in the 1s0d model space with some effective Hamiltonian. Perturbative calculations of higher-order configuration mixing and Δ isobar mixing[13] are able to quantitatively account for the quenching observed in the 1s0d shell.[14] That is, if one were to compare the experimental strength with calculations which include both the 0s1d model space plus these higher-order effects (either explicitly, or implicitly in terms of an effective operator), there would agreement between experiment and theory.

There is not a clear cut division between the GT strength which resides primarily on the 1s0d model space and in the direct contribution due to higher-order configuration mixing in the ground state. In particular, the direct strength ascribed to the lowest energy two-particle two-hole $2\hbar\omega$ admixture is observed in a few discrete states around about 10 MeV in ^{40}Ca. The experimental B(GT) in the strongest of these as deduced from a ^{40}Ca(p,n) experiment is only 0.33±0.06,[15] and calculations with the SAS interaction[16] in the $0d_{3/2}$-$0f_{7/2}$ model space, which reproduces the observed B(M1) for these states,[17] predicts a total of only B(GT)=0.8. The same type of calculation predicts an extra amount of strength $B(GT^{+})=0.8$ for the ^{37}Ca β^{+} decay. This is small compared to the 1s0d contribution. It also predicts $B(GT^{-})=0.08$ (rather than zero), which is a factor of four smaller than the strongest state observed in ^{40}Ca(p,n). [Note that the 3(N-Z) sum rule does not hold within the $0d_{3/2}$-$0f_{7/2}$ model space, and that these results can be interpreted, at best, as an indication of the strength expected in the lowest few discrete states.] A ^{37}Cl(n,p) experiment would be useful to confirm this. Of course, one should expect even more GT strength at higher excitation energy within the full 1s0d-1p0f model space as well as more from higher $\hbar\omega$ correlations. However, this strength is difficult to extract from charge-exchange reactions because of the dominance of higher multipole excitations at higher excitation energy. I believe that the GT strength observed below 15 MeV in excitation for A<40 should be ascribed primarily to the 1s0d model space. Finally, I note that the $n\hbar\omega$ excitations greatly increase the level density compared to that expected from the $0\hbar\omega$ 1s0d configurations. This most clearly shows up in the spreading of the $0d_{5/2}$ hole strength in A=39[9,10] and in the high level density observed in the ^{37}Ca beta decay (between 5 and 8 MeV about 3 times that expected in the 1s0d model space).

In conclusion I find that the amount of quenching extracted from the ^{37}Ca β^+ decay data is very sensitive to the shape assumed for the GT strength distribution. If the old (p,n) data is taken an indication of what this shape is, then I find that calculations with the 12.5p or CW Hamiltonians are preferred and that the quenching inferred from the β^+ decay is about the same as obtained from the global analysis of all 1s0d-shell beta decay data. A further evolution of the 1s0d-shell Hamiltonian which would incorporate both the success of the W Hamiltonian across the shell and the CW interaction for the Gamow-Teller distribution in the upper part of the shell will remain a challenge.

Acknowledgements

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Caption to Fig. 1

B(GT$^+$) strength distribution for ^{37}Ca. The dashed line is the strength extracted from experiment, and the solid lines correspond to various theoretical calculations (see text for details).

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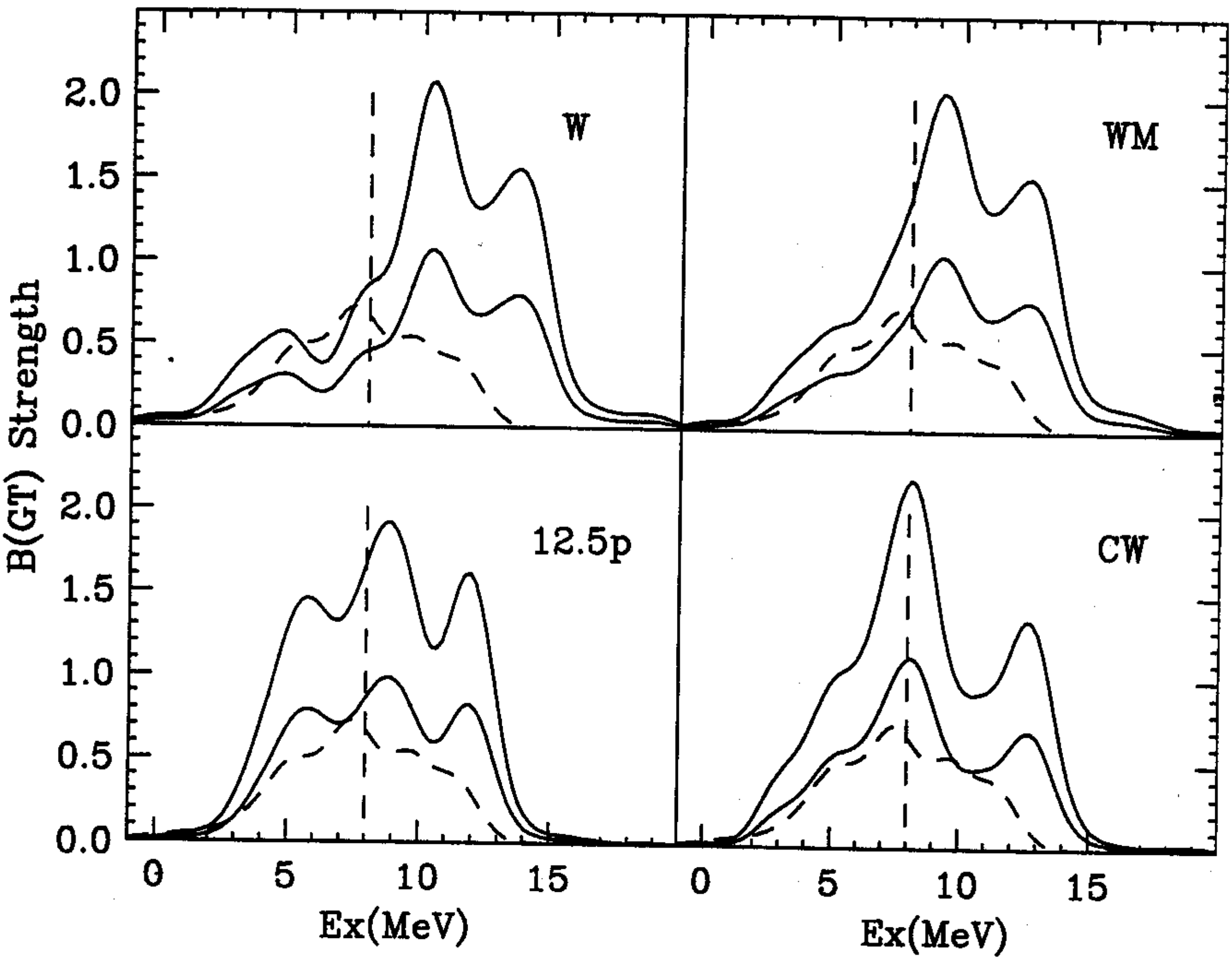
B(GT) Strength
2.0
1.5
1.0
0.5
0.0
W
WM
12.5p
CW
0
5
10
15
Ex(MeV)