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GAMOW-TELLER STRENGTH IN LIGHT NUCLEI

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ABSTRACT

Matrix elements for the Gamow-Teller operator $\sigma\tau$ extracted from experimental beta decay and reaction data provide an important test for nuclear structure models. I will discuss the comparison of new experimental data, in particular those from the beta decay of the most proton- and neutron-rich nuclei, to current shell-model calculations. The comparisons will include detailed strength distributions as well as the overall hindrance factors. The origin of the hindrance factor, the reduction in the overall experimental strength in low-lying states relative to $0\hbar\omega$ (or truncated $0\hbar\omega$) shell-model calculations, will be discussed. I also discuss the isospin breaking corrections to Fermi transitions and the nature of "Super" Gamow-Teller transitions in nuclei up to ^{100}Sn.

1. Introduction

The study of allowed β decay in nuclei is important for testing nuclear structure models as well as for predicting the weak interaction rates needed for astrophysical processes and double beta decay. The decay rate for allowed β^-/β^+ decay is given by $ft_{1/2} = 6170/[(g_A/g_V)^2 B(GT_{-/+}) + B(F_{-/+})]$, where f is the phase-space factor, $t_{1/2}$ is the partial half-life for the decay from an initial state (Ψ_i) to a specific final state (Ψ_f), $B(GT_{-/+}) = |< \Psi_f \; || \; \Sigma_k \sigma^k t^k_{+/-} \; || \; \Psi_i >|^2 \; /(2J_i + 1)$ is the reduced Gamow-Teller transition rate, and $B(F_{-/+}) = |< \Psi_f \; || \; \Sigma_k t^k_{+/-} \; || \; \Psi_i >|^2 \; /(2J_i + 1)$ is the reduced Fermi decay transition rate. The g_A/g_V is the ratio of the axial-vector to vector coupling constants for the nucleon as obtained from the neutron beta decay, and t_+ and t_-, are the nucleon isospin raising and lowering operators, respectively.

The reduced transition rates satisfy the sum rules $S(F) = \Sigma_f B(F_-) - \Sigma_f B(F_+) = (N - Z)$, and $S(GT) = \Sigma_f B(GT_-) - \Sigma_f B(GT_+) = 3(N - Z)$. When isospin is conserved, the Fermi decay goes only to the isobaric analog state. When $| T_{zi} | = T_i$ then either $B(F_-)$ or $B(F_+)$ is zero and the reduced rate for the other is $| N - Z |$. There is a small isospin nonconserving part to the nucleon-nucleon interaction due to the Coulomb and charge-dependent nuclear interactions, and this leads to a small correction to the Fermi matrix element which is conventionally expressed in the form $\tilde{B}(F) = (1 - \delta_c)B(F)$. The results of a recent calculation [1] for the correction factors δ_c are shown in Fig. 1 (crosses connected by a line) and compared to the experimental values (filled circles) for those $0^+ \rightarrow 0^+$ (pure Fermi) decays which have been measured with high accuracy. [2,3] The experimental values have been adjusted by an overall factor to fit the calculations for the lowest Z values. On an absolute scale, the experiment and theory deviate (from the unitarity of the KM matrix) by 0.3-0.4 percent. [2,4,5]

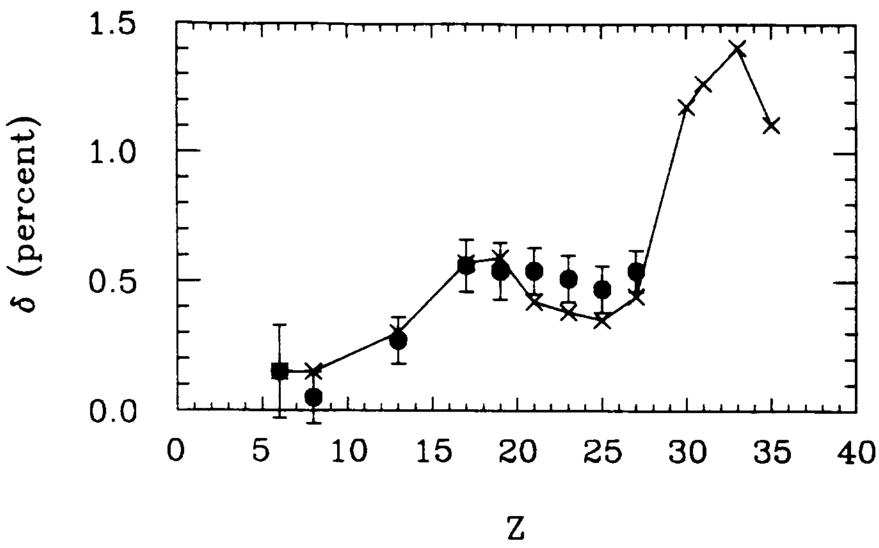

Figure 1: Isospin mixing correction to Fermi transitions.

The reason for this deviation is not understood. The new aspect of the calculations presented in Fig. 1 is the prediction of a jump in the δ_c value at Z=30 and above. Experiments for these higher Z nuclei would provide a useful test of these nuclear corrections.

When the nucleon intrinsic spin is conserved, the GT transitions can go only to a single final state which we might call the GT analog. Of course, the nucleon-nucleon interaction strongly violates this symmetry and the total strength $3(N-Z)$ is strongly split among many states in both the β^- and β^+ direction. It is the role of nuclear models to predict this splitting.

2. GT Strength in the 0d1s Shell

One of the most comprehensive and systematic calculations of GT strength has been carried out for the 0d1s shell nuclei.[6] The shell-model calculations were carried out in the full 0d1s model space with the USD Hamiltonian.[7] In Ref 6 the comparison between theory and experiment was made for hundreds of individual transitions. Here I want to emphasize the systematics of these comparisons with some comments on more recent results. In Fig. 2 the total GT strength $\Sigma_f B(GT)$ obtained from either β^- or β^+ beta decay of 0d1s shell nuclei are compared with theory. The experimental sum is limited to those states which lie within the beta decay Q value windows and the same energy cut-off was used for the theory. The summed strength is divided by $3(N-Z)$, so that a point at unity on the scale of Fig. 2 would exhaust the sum rule. (Of course the summed GT strength for either β^- or β^+ by itself could exceed the sum-rule value.) Most points in Fig. 2 are smaller than unity because only a fraction of the total GT strength lies within the Q value window. The two points

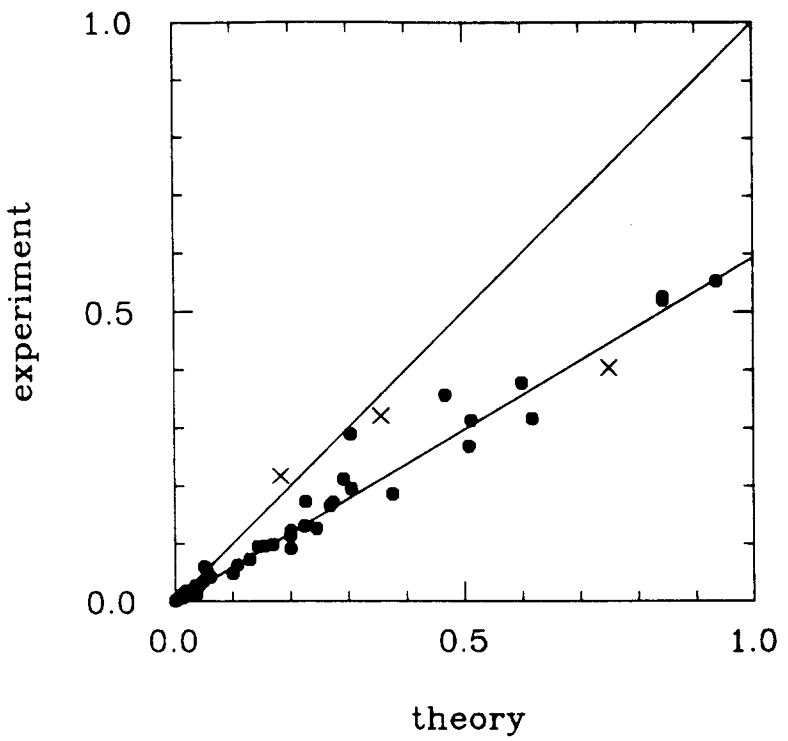

Figure 2: Comparison of experimental and theoretical Gamow-Teller strength.

in Fig. 2 for which most of the calculated strength lies within the Q value window are for A=18 and A=19. The striking aspect of the comparison in Fig. 2 is that the theory and experiment do not agree (they do not lie on the 45 degree line) but that the experiment strength is systematically smaller than the theoretical strength (quenched) by a factor of about 0.59 – as represented by the line in Fig. 2 which goes through the average of the data. That is, the experimental beta decay is hindered by a factor of 1.67 compared to theory. Where is the missing strength? Maybe it has been missed in the β decay because the strength is shifted to higher energy states above the Q value window. The (p,n) experiments provide important complimentary information in this regard. For example, the strength for the ^{18}Ne beta decay (one point in Fig. 2) can be compared with the strength observed in the mirror ^{18}O(p,n) reaction.[8,9] Examination of the spectrum of Fig. 7 of Ref 8 shows that the GT strength distribution (into the sharp states) is much like the predicted one. Detailed analysis of such spectra[9] show that the observed GT strength distribution agrees with that predicted by the 0d1s shell-model calculations and that the missing strength is not to be found in sharp states below 20 MeV of excitation.

This quenching factor of about 0.6 appears to be rather universal as long as a complete $0\hbar\omega$ model space (e.g. full 0d1s) is used. Calculations within the full 0f1p shell require about the same reduction factor in order to reproduce the observed GT β decay.[10,11,12] Much theoretical work has been done to understand the origin of the

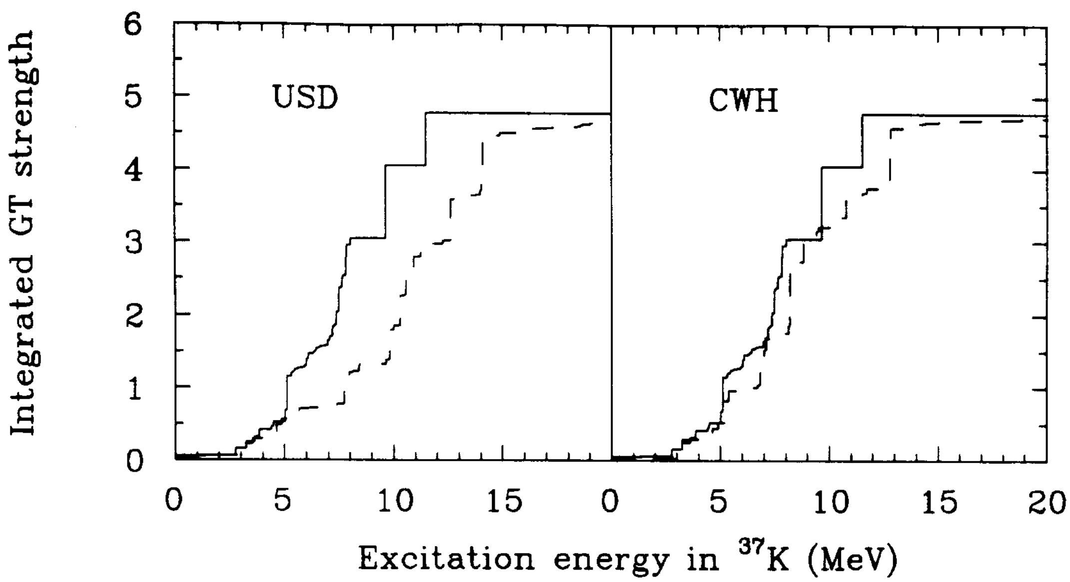

Figure 3: Gamow-Teller strength in the decay of ^{37}Ca

quenching.[13] From comparison of M1 and GT matrix elements, one can deduce that about two-thirds (in the amplitude) of this comes from higher-order configuration mixing (from non-sd shell parts of the wave function) while one-third comes from the delta-particle nucleon-hole admixture.[14] The position of the missing strength and its division between β^- and β^+ related to the higher-order mixing is unclear but is presumably spread out over excitation energies up to about 100 MeV, making it very difficult to observe experimentally.

Since the data compilation of Ref 6 (shown in Fig. 2 by the circles) there have been several important experimental improvements In particular, much improved data have become available for the Ca isotopes (shown in Fig. 2 by the crosses going from left to right for ^{36}Ca, ^{37}Ca and ^{38}Ca). The first observation from the ^{37}Ca decay data[15] was that the experimental strength (up to the Q value window energy of 8 MeV) was not quenched but was near to the free nucleon value (near the 45 degree line in Fig. 2). The detailed strength distribution is shown in Fig. 3 as a running sum of the GT strength vs excitation energy. The experiment[16,17] (solid line) is compared with the USD calculation (dashed line) on the left-hand side. However, the ^{37}Ca beta decay "sees" only about 30 percent of the sum-rule value $S(GT)$=9. Again, one must rely on the mirror ^{37}Cl(p,n) data to give some indication about the strength above 8 MeV. The strength reported in Ref 18 renormalized to the total strength observed in β decay below 8 MeV is indicated by the solid line steps from 8-12 MeV in Fig. 3. It appears that the total GT strength is still quenched but that the peak is experimentally about 3 MeV lower than theory. In Ref 19 I pointed out that there existed an older shell-model interaction for the upper part of the 0d1s shell (the Chung-Wildenthal hole interaction) which puts the peak of the GT strength at a lower

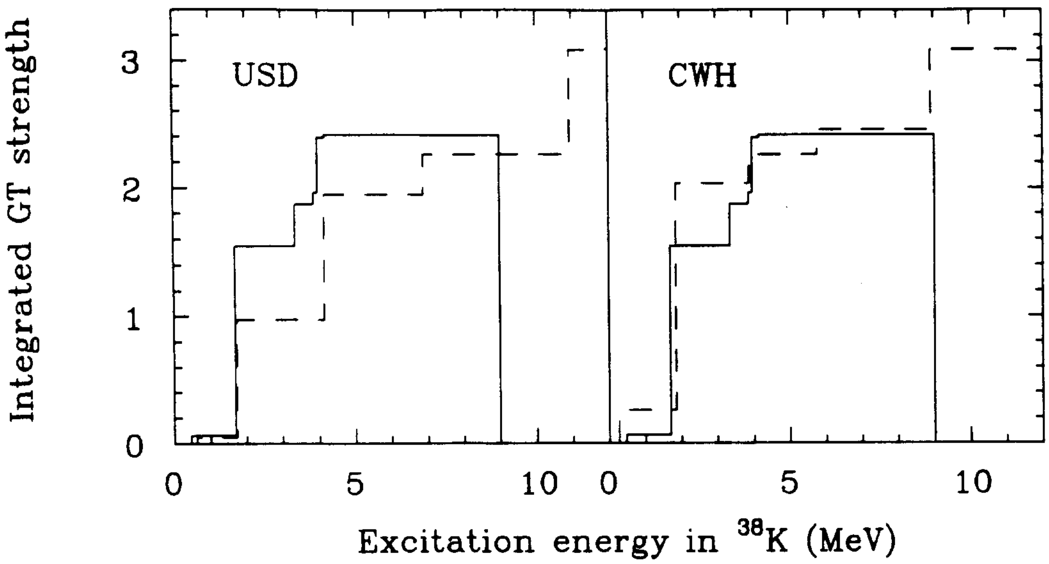

Figure 4: Gamow-Teller strength in the decay of ^{38}Ca

energy in better agreement with experiment as shown by the comparison with CWH on the right-hand side of Fig. 3. One can question the reliability of the absolute GT strength obtained from the (p,n) reaction data. There is some disagreement between β decay and (p,n) data for the individual low-lying states.[17]

New data[20] for ^{36}Ca show the same trend as ^{37}Ca when compared with the USD interaction. But again the Q value window limits the data to states below about 8 MeV where only 22 percent of the sum-rule value $S(GT)$=12 is observed. The CWH interaction again moves the peak energy down in better agreement with experiment. The mirror ^{36}S(p,n) reaction, which would determine the higher lying GT strength, has not yet been carried out.

The new data for the ^{38}Ca decay are particularly exciting.[21] The GT strength obtained from this experiment are compared in Fig. 4 with the USD and CWH interactions. The Q value window limits the final states to below about 4 MeV in excitation, however, the total strength of 2.4 observed is 40 percent of the sum-rule value $S(GT)$=6. In addition, the mirror ^{38}Ar(p,n) data[22] is exceptionally clean and shows no more significant GT strength up to about 8 MeV (where the solid line in Fig. 4 cuts off). The CWH state at 9 MeV is the transition to a 1^+,T=1 state (the lower strength is all to 1^+,T=0 states). The 1^+, T=1 final state has been studied in the ^{38}Ar(e,e′) reaction[23] and observed to be fragmented over an excitation range of 7-14 MeV. This fragmentation is due to 2p(0f1p)-2h(0d1s) intruder states. It is possible that these intruder states may effect the width and position of the GT resonance.

The influence of the energy shift between the USD and CWH interactions for the β^+ decay of the proton-rich Ar isotopes has been discussed by Borge et al.[24] (the circle near the 45 degree line in Fig. 2 with a theory value of about 0.3 is for

^{34}Ar). The strength distributions of the GT strength obtained from (p,n) data for nuclei in the lower and middle part of the 0d1s shell is in good agreement with the USD predictions.[7] A modified Hamiltonian which can reproduce the GT strength distributions throughout the 0d1s shell has yet to be found.

3. Super Gamow-Teller Transitions

By "Super" Gamow-Teller transition I will mean a GT transition to a specific final state which has a large $B(GT)$ value compared to the bare nucleon (neutron decay) value of $B(GT)$=3. Although the sum-rule value can be quite large in nuclei with a large neutron excess, it is not easy to find many examples of Super GT transitions. For example, for the GT_- transition from ^{208}Pb, which has been studied with the intermediate energy (p,n) reaction, the GT_+ should be small (because of the neutron excess) and hence $\Sigma_f B(GT_-) \approx 132$. However, for ^{208}Pb as well as most other cases observed, the total Gamow-Teller strength is fragmented over many final states, hence the GT strength to any specific final state is small.

In fact, there are only two transitions to specific final states observed so far which are larger than the neutron value of 3. They are 0^+, T=1, ^6He to 1^+, T=0, ^6Li decay with $B(GT_-)$=4.72[25] and the 0^+, T=1, ^{18}Ne to 1+, T=0, ^{18}F decay with $B(GT_+)$=3.15.[6] The reduction from the sum-rule values of $S(GT) = 6$ are due to the quenching discussed above. In both of these examples, the final states are ground states and they come low in energy because of the attractive particle-particle interaction. As one moves away from the two-particle valence case and adds more valence particles, the strong GT strength moves up in energy and eventually becomes a "particle-hole" state which is pushed up by the residual particle-hole interaction. The high energy usually results in a fragmentation of strength due to mixing with 2p-2h configurations. Borge et al.[26] have presented the case for "Super" GT strength in the decays of ^8He, ^9Li and ^{11}Li. However, since the final states lie at a high excitation energy, the strength is probably fragmented over many final states. 0p shell calculations for the ^9Li and ^{11}Li decays show this fragmentation.[27] 0p shell calculations[25] for the ^8He decay predict a strength of 7.7 for a state at about 9 MeV in excitation,[25] but the experiment is difficult to interpret because of the large width of the final state.

Where should we look for other example of Super Gamow-Teller transitions? I believe there are two candidates – ^{56}Ni and ^{100}Sn. ^{56}Ni is known to decay to a low-lying final state in ^{56}Co, but the Q value is very small and this particular final state has a very small $B(GT)$. We have predicted[28] a Super GT to a level just above the Q value with $B(GT) \approx 5.5$ which may be studied via the inverse reaction p(^{56}Ni,^{56}Co)n. Also, we have predicted[29] that ^{100}Sn should beta decay by a Super GT to a low-lying state in ^{100}In with $B(GT) \approx 8.5$.

The GT strength of ^{56}Ni and ^{100}Sn are both examples of a general class of transitions in nuclei with N=Z.[30] The N=Z nuclei are interesting because the GT sum rule only gives $\Sigma_f B(GT_-) = \Sigma_f B(GT_+)$; a result of isospin symmetry. There are thus several equivalent ways to obtain the $B(GT)$ values in N=Z nuclei; β^+ decay (where energetically allowed) or (n,p) reactions, β^- decay or (p,n) reactions, or (p,p′) reactions. As one approaches ^{100}Sn, the beta decay Q values become larger due to the larger Coulomb displacement energy,[31] hence much more of the GT strength can be observed in β decay. Data for the interesting region between ^{56}Ni and ^{100}Sn will rely upon future radioactive beam experiments. The $\Sigma_f B(GT)$ are thus completely model dependent and turn out to be extremely sensitive to nuclear correlations.[30]

Calculations for ^{56}Ni[28] and ^{100}Sn[29] at the level of 2p-2h $0\hbar\omega$ correlations indicate that GT strength in these nuclei should be strong and concentrated into single low-lying final states. The strength is due to the fact that the high-ℓ orbital with j=ℓ+1/2 is completely filled and the orbital for j=ℓ-1/2 is completely empty (in the extreme single-particle model). The results for ^{100}Sn are particularly interesting. We predict[29] a Q value of 7.0 MeV for the decay to a final state at an excitation energy of 1.8 MeV with $B(GT)$ $\approx$8.5 and $T_{1/2}$ $\approx$0.5 s. The final state is low enough above the proton decay threshold that it should decay entirely by gamma emission. The first experimental indications[32] are in agreement with the prediction, but a much more accurate experiment with gamma coincidence will be required to determine whether or not this is indeed an example of a Super GT transition. It is important to understand the origin of quenching in heavier nuclei. Only recently[12,33] has it become possible to calculate the total GT strength in a full 0f1p shell basis for nuclei such as ^{56}Ni, and we will soon have a better understanding of the role of correlations beyond the 2p-2h (RPA) level.

4. Acknowledgments

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