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Giant Gamow-Teller Excitation of ^{148}Dy Populated in β^+ Decay

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A precise study of ^{148}Dy Gamow-Teller β^+ decay gives 97% direct feeding to the $(\pi h_{11/2} \nu h_{9/2})1^+$ state in the daughter nucleus ^{148}Tb, corresponding to $\log ft = 3.95(3)$. The transition strength is only 15% of the value calculated with the quasiparticle random-phase approximation, which takes into account pairing effects and ground-state correlations. The strength reduction is significantly larger than found in other $\pi j_> \rightarrow \nu j_<$ Gamow-Teller β^+ decays.

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Since the first clear observation[1] of Gamow-Teller (GT) resonances in (p,n) experiments these excitations have been systematically located over a wide range of nuclei. Whereas the observed energies are in agreement with theoretical predictions, it was found that the strengths are significantly smaller[2] than predicted by estimates based on the $S^- - S^+ = 3(N-Z)$ sum rule, and various ideas to understand the missing strength in terms of high-energy excitations have been intensively discussed in the past few years. In particular, isobar excitations[3] at $E_x = 300$ MeV and tensor-type correlations[4] in the 10- to 50-MeV region have been considered, but at present these excitations are not accessible to direct experimental test.

It would be desirable to complement the (p,n) results through studies of β^- decay since the β-decay process is simpler and quantitatively better understood than the (p,n) reaction. Moreover, energy resolution and detection sensitivity are 100 to 1000 times better in β-decay studies than can be achieved in nuclear reaction measurements. However, in all β^--decaying nuclei the giant GT$^-$ resonance[5] is energetically not accessible in decay. In contrast, for neutron-deficient nuclei the GT$^+$ resonance can be populated in β^+ decay, although until now only a few (n,p) studies have been done[6] to locate the GT$^+$ giant state. Since in these nuclei the proton single-particle states are raised through Coulomb repulsion, it may become possible to excite the GT$^+$ giant state in β^+ decay whenever the proton and neutron Fermi energies are between the spin-orbit partners of a high-l orbit, i.e., such that the $j_>$ state is partly filled by protons whereas the $j_<$ state for neutrons is (partly) empty. This condition is fulfilled for the 1g shell in the $N \geqslant 50$ nuclei below ^{100}Sn, and for the 1h orbitals in the $N \geqslant 82$ nuclei above ^{146}Gd, and in both regions such $nj_> \rightarrow \nu j_<$ GT β^+ decays have been identified. Since, e.g., in nuclei with 82 neutrons all $N=4$ neutron states are filled, the Pauli principle only allows a $\sigma\tau_+$ transition of the $N=5$ $h_{11/2}$ protons to the unoccupied $h_{9/2}$ neutron orbit. If we disregard ground-state correlations in the parent nucleus, this is the only possible $\sigma\tau_+$ transition which will exhaust the entire available strength and thus the $(\pi j_> \nu j_<)1^+$ state in the daughter nucleus is identical with the GT$^+$ giant state. We therefore use the name "giant state," although the transition is not very strong, involving only a few active particles. The nature of this GT$^+$ state is similar to the $M1$ giant resonance[7] excited by the $\sigma\tau_0$ operator, which in a doubly closed nucleus is composed of two specific transitions, viz., the transitions connecting the spin-orbit partners for protons and neutrons on opposite sides of the Fermi levels. The principal locations of the pertinent states for the $N=82$ region are shown in Fig. 1, which refers to the ^{148}Dy case investigated in the present study. The figure also includes the isobaric-analog state at its estimated excitation energy and the GT$^-$ resonance based on the ^{148}Gd$_{84}$ ground state, which should lie about 2 MeV higher.

Since the original investigation[8] of ^{148}Dy$(0^+) \rightarrow {}^{148}Tb(1^+)$ GT decay, there have been several[9,10] additional studies of this and of other $N=82$ even nuclei with similar characteristic decays. More recently, measurements of EC/β^+ ratios were used to determine the Q_β values, and it was noted[10] that the observed $0^+ \rightarrow 1^+$ GT transition strengths are strongly retarded compared to the shell-model prediction for $(\pi h^n_{11/2})0^+ \rightarrow (\pi h^{n-1}_{11/2} \nu h_{9/2})1^+$ transitions. All these investigations however have identified a single γ ray only, viz., the $(1^+ \rightarrow 2^-)$ $E1$ ground-state transition in the odd-odd daughter, and therefore it remained

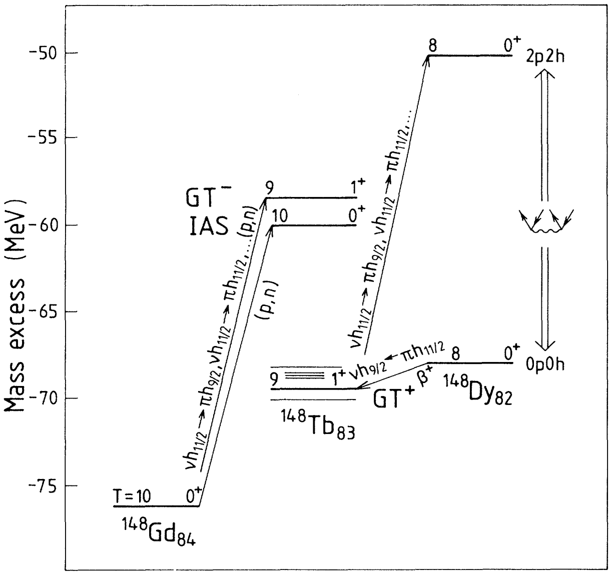

FIG. 1. Schematic representation of the $T=9$ GT^+ and GT^- giant states in ^{148}Tb and of the $T=10$ analog state of the ^{148}Gd ground state. Energies of the unobserved high-lying levels are estimated from data in neighboring nuclei. The excited two-particle, two-hole (2p-2h) 0^+ state in Dy created by the combined action of the $\sigma\tau_+$ and $\sigma\tau_-$ operators mixes into the ground state (ground-state correlations). The interaction matrix element has the sign such that the admixture causes a reduction of the transition matrix element to the GT^+ state in Tb.

unknown whether additional GT strength lies at higher excitation within the Q_β window. The present study elucidates this question for ^{148}Tb which we have investigated through more precise measurements with substantially increased sensitivity allowing detection of γ transitions with an intensity as low as 10^{-4} per decay.

The ^{148}Dy was produced through (^{3}He,xn) reactions with use of a 240-MeV ^{3}He beam of 1.5 μA on an 8-g natural Gd target located in the ion source of the ISOCELE II on-line mass separator[11] at the Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse, Orsay. The separated $A=148$ ions were deposited on a tape and transported with suitably chosen cycles to the detectors. The experiments included decay measurements in multispectral scaling mode, and $\gamma\gamma$ and γ–x-ray coincidences with two 20% Ge(Li) detectors and a planar Ge detector. Conversion-electron spectra were measured with a Si(Li) spectrometer in a wide-range magnetic electron selector,[12] which provided α_K values for transitions up to 1.3 MeV with intensities $\geqslant 2\times 10^{-3}$ per decay.

These data gave the ^{148}Dy decay scheme of Fig. 2, where fourteen new ^{148}Tb energy levels with firm I^π assignments or with narrow limits are identified. The proposed shell-model configuration assignments will be discussed in a forthcoming article. It was found that 97% of the β-decay intensity feeds the 620-keV 1^+ state which is the GT^+ giant excitation on the ^{148}Dy ground state. Four $I=1$ levels are observed close to 1.3 MeV, with positive parity measured for the lowest one at 1.247 MeV. One 1^- state should lie in this energy region, and we prefer to assign it to the 1.333-MeV level. Positive parity is suggested for the two remaining levels on account of the two additional 1^+ configurations expected at this energy. The higher-lying $I=1$ levels have firm negative parity from α_K data except the 1.828-MeV state where the parity remains undetermined.

The logft values are calculated with the ^{148}Dy half-life and Q_β value quoted in the figure which are both adopted mean values from independent[8-10] measurements. By use of the relation[13]

$$B(\mathrm{GT})=\tfrac{1}{2}\pi^2\hbar^7 m_e^{-5}c^{-4}(\ln 2)(ft)^{-1}$$
$$-(3880g_A^2/4\pi)(ft)^{-1},$$

the log$ft=3.95(3)$ for the 620-keV state corresponds to

$$B(\mathrm{GT},0^+\rightarrow 1^+)=0.44(3)g_A^2/4\pi,$$

or 12% of the shell-model prediction calculated as

$$B_{\mathrm{SM}}(\mathrm{GT})=n\frac{4l}{2l+1}\frac{g_A^2}{4\pi}=3.6\frac{g_A^2}{4\pi},$$

assuming $n=2h_{11/2}$ protons in the ^{148}Dy ground state.

An important result of our study is the almost complete absence of additional GT^+ strength in ^{148}Tb below 2.3 MeV as is shown in Fig. 2 to the left; the summed strength to the three higher-lying 1^+ states is $\leqslant 0.02g_A^2/4\pi$. Also shown in the figure is a conservative experimental strength-sensitivity limit corresponding to 0.1% β feed, ten times higher than the weakest γ transitions observed in the decay. Our results demonstrate that mixing of the giant GT^+ state with background 1^+ levels of other configurations is very small in ^{148}Tb.

The GT^+ strength retardation of a factor 8 found here for ^{148}Tb is unexpectedly large. The result, however, agrees with the retardations deduced from less conclusive data for higher-Z $N=82$ isotones.[10]

The quoted strength retardation is based on the shell-model estimate with the assumption of two $h_{11/2}$ protons in the ^{148}Dy ground state. We will consider two effects which modify the strength prediction significantly. First, it is known from experiment that proton pairs scatter across $Z=64$ in the ground states of ^{146}Gd and its neighbors. This is evident from single-proton-transfer measurements[14] on a $^{144}_{82}$Sm target which suggest that $1.6(3)h_{11/2}$ protons are present in

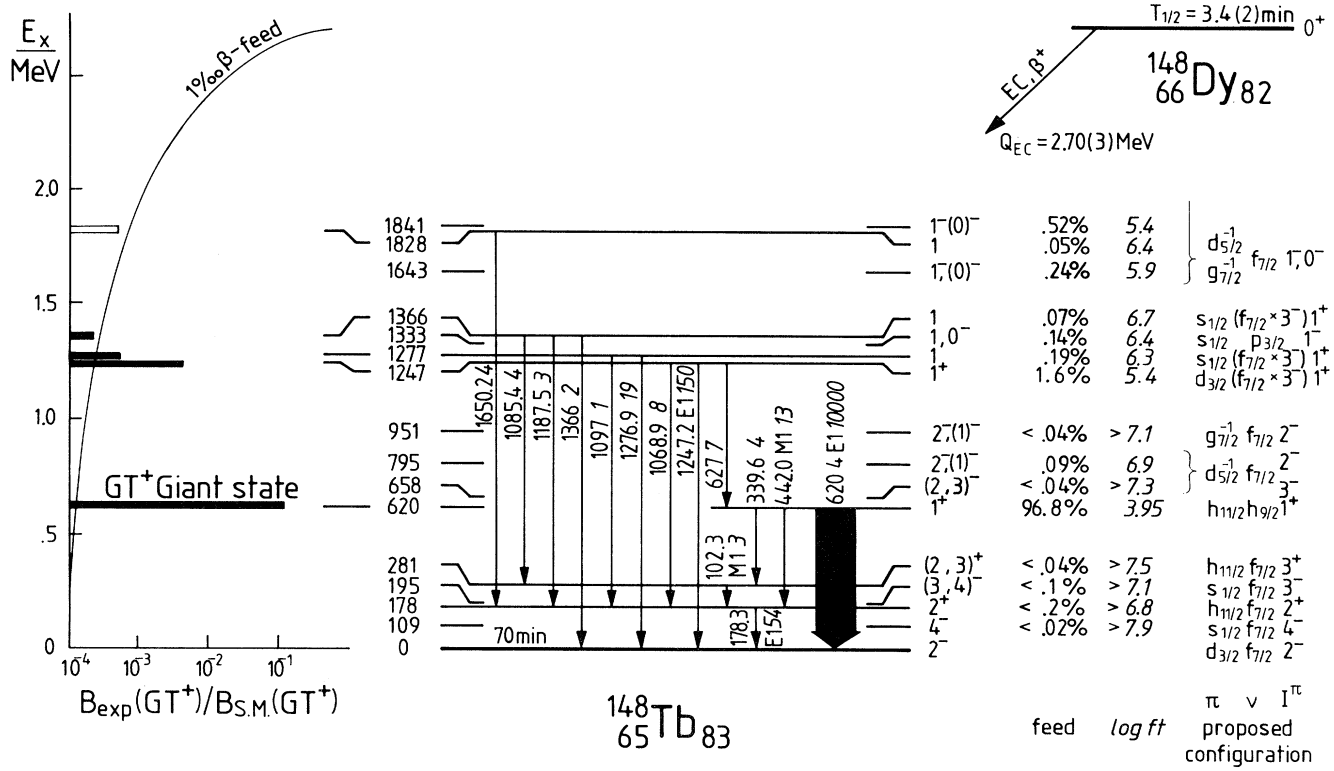

FIG. 2. Levels in ^{148}Tb observed in the decay of ^{148}Dy. Deexcitation γ rays are shown only for firm and possible 1^+ states. Transition multipolarities derived from α_K values are given together with the γ-ray energies and intensities. The measured GT$^+$ transition strengths to identified 1^+ levels are plotted to the left where also the detection sensitivity limit for 1^+ strength is included.

its ground state. This pair scattering will raise the number of $h_{11/2}$ protons in ^{148}Dy above two, leading to a larger strength prediction. Significant strength reduction is expected, however, from ground-state correlations in the ^{148}Dy parent nucleus. These correlations are due to mixing with two-particle, two-hole states involving one $\nu^{+1}\pi^{-1}$ and one $\pi^{+1}\nu^{-1}$ excitation which are formed by the $\sigma\tau_+$ and $\sigma\tau_-$ operators, respectively (cf. Fig. 1). One important component of this type of admixture to the ground state is, e.g.,

$$[(\nu h_{9/2}\pi h_{11/2}^{-1})_{1^+}(\pi h_{9/2}\nu h_{11/2}^{-1})_{1^+}]0^+.$$

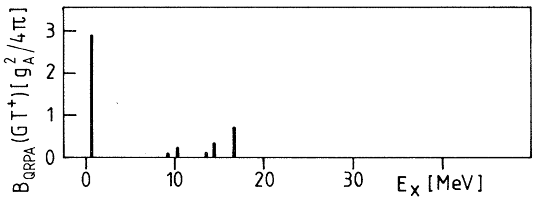

FIG. 3. The $\sigma\tau_+$ strength in ^{148}Tb from a QRPA calculation. The excitation energy has been shifted to reproduce the position of the lowest 1^+ level at 0.620 MeV.

In ^{148}Dy these states are expected to lie at 10 MeV excitation or higher and it is easy to verify that such correlations should be quite significant for the specific proton and neutron Fermi energies in ^{148}Dy.

Both these effects are explicitly taken into account in the ^{148}Tb GT$^+$ strength of Fig. 3, which is calculated by the quasiparticle random-phase approximation (QRPA). Here the protons in the ^{148}Dy ground state are described by the BCS vacuum, whereas the $N = 82$ neutron shell is considered to be closed. The single-particle basis is taken from Conci *et al.*,[15] and the parameters for the pairing force[16] were chosen as $h^{\text{in}} = -243$ and $h^{\text{ex}} = -1112$ MeV fm^3 to reproduce the measured[14] $\pi h_{11/2}$ occupation probabilities. For ^{148}Dy, $v^2(h_{11/2}) = 0.26$ results, corresponding to 3.2 $h_{11/2}$ protons, significantly larger than in the above shell-model estimate. To calculate the 1^+ states in ^{148}Tb we use[16] for the particle-hole interaction a zero-range force of the Migdal type plus a finite-range contribution deduced from one-boson exchange potentials. The *pp* interaction is chosen equal to the density-dependent pairing force used to solve the BCS equations. The $\sigma\tau_+$ strength is calculated as

$$B(\text{GT}^+) = |\textstyle\sum_{\nu\pi}(X_{\nu\pi}u_\nu v_\pi - Y_{\nu\pi}v_\nu u_\pi)\langle\sigma\tau_+\rangle|^2,$$

where the X and Y are the forward- and backward-transition amplitudes obtained as solutions of the QRPA equations, and u and v are the occupation factors. The ground-state correlations are specified by the Y's and give rise to a reduction of the GT$^+$ transition strength. Our calculation gives 0.53 for the strength reduction factor due to ground-state correlations in the ^{148}Dy parent nucleus. This result is in close agreement with an independent estimate based on perturbation theory[17] where retardation factors between 0.39 and 0.50 for various choices of the effective interaction were deduced. With the inclusion of pairing effects and ground-state correlations the GT$^+$ strength for the lowest 1^+ state in ^{148}Tb is $B_{\mathrm{QRPA}}(\mathrm{GT}^+, 1_1^+) = 2.94 g_A^2/4\pi$, and thus the experimental retardation becomes

$$B_{\mathrm{exp}}(\mathrm{GT}^+)/B_{\mathrm{QRPA}}(\mathrm{GT}^+) = 0.15,$$

where the uncertainty of the theoretical analysis is believed to be of the order of 30%. By accident, this result is quite similar to the shell-model estimate since for ^{148}Dy the strength modifications caused by pairing effects and by ground-state correlations are of comparable magnitude and opposite sign.

The strength retardation factor of 0.15 for ^{148}Tb is significantly smaller than found for other GT β^+ decays. The analogous $\pi g_{9/2} \rightarrow \nu g_{7/2}$ GT$^+$ transitions were studied[18] in the $^{94}_{44}\mathrm{Ru}_{50}$ and $^{96}_{46}\mathrm{Pd}_{50}$ decays where, in contrast to ^{148}Dy, the β^+ decay strongly feeds several low-lying 1^+ levels in the odd-odd daughter nuclei. The combined observed strengths are respectively 0.14 and 0.22 of the shell-model estimates for four and six $g_{9/2}$ protons. With the calculated corrections[17] for pairing and ground-state correlations, the observed strength fractions become ~ 0.49 for ^{94}Ru and ~ 0.61 for ^{96}Pd, 3 to 4 times bigger than the corresponding 0.15 found in ^{148}Tb. A similar result was derived in a study[19] of β^+ decay of the $N < Z$ nucleus ^{32}Ar, where the observed strength fraction was 0.30. For this case a full shell-model calculation was performed which suggests that 62% of the total GT$^+$ strength lies within the Q_β window in the ^{32}Cl daughter nucleus, giving a corrected retardation factor of 0.49, close to the two $\pi g_{9/2} \rightarrow \nu g_{7/2}$ cases. These results are in accord with the missing strength found for a wide range of nuclei from (p,n) experiments as quoted in one review article[2]; however, the quantitative interpretation of the (p,n) cross sections is at present still[20] under discussion.

In conclusion, our measurements show that 97% of ^{148}Dy β^+ decays populate the GT$^+$ giant state at 0.620 MeV in ^{148}Tb. Three close-lying identified 1^+ levels receive less than 2% of the decay intensity, indicating small mixing with the GT$^+$ level. By comparison with a theoretical analysis which takes account of proton pairing effects and of ground-state correlations in the ^{148}Dy parent nucleus, it is concluded that only $\sim 15\%$ of the expected GT$^+$ strength resides in the 0.620-MeV state and that no appreciable strength should occur above it. The strength retardation in ^{148}Tb is considerably larger than that found for nuclei in other regions. This fact is difficult to reconcile with the concept of missing strength due to the coupling to high-energy excitations. Alternatively, it cannot be ruled out that coupling to still inconceived types of low-energy excitations also contributes to the GT$^+$ strength reduction in ^{148}Tb.

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