Strongly Excited 0^+ States Observed in (p, t) Reactions on Gadolinium Nuclei

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A single low-lying 0^+state is observed with about 15% of the ground-state strength in the reactions $^{160,158,156}\mathrm{Gd}(p,t)^{158,156,154}\mathrm{Gd}$ at 18 MeV. The change in shape at $N=88$ is observed in the reaction $^{154}\mathrm{Gd}(p,t)^{152}\mathrm{Gd}$, with two excited 0^+ states being strongly populated. A similar change in the Sm nuclei has been observed earlier. An excited 0^+ state is observed in the reaction $^{152}\mathrm{Gd}(p,t)^{150}\mathrm{Gd}$ with ~ 10% of the ground-state strengths.

In this Letter we report on (p,t) data obtained in the stable even-even Gd nuclei. The final nuclei span the region from spherical $(A=150)$ to deformed $(A=158)$ and include the "quasirotational" nucleus $^{152}\mathrm{Gd}$; the reaction $^{154}\mathrm{Gd}(p,t)$-$^{152}\mathrm{Gd}$ crosses the region of nuclear deformation at neutron number $N=88$. A study of the (p,t) reaction on the Gd nuclei complements the information already known from (t,p) and (p,t) reactions on the neighboring Sm nuclei[1,2] and (p,t) reactions on the Yb nuclei,[3] and thus provides additional cross-section systematics for two-neutron transfer reactions in this mass region. Only the 0^+ and 2^+ final states are populated with appreciable strength, although some states of higher spin are also observed.

The experiments were carried out using the 18-MeV proton beam from the tandem accelerator of the Niels Bohr Institute. Outgoing tritons were detected in photographic emulsions placed in the focal plane of the magnetic spectrograph. Spectra from the reactions $^{158}\mathrm{Gd}(p,t)^{156}\mathrm{Gd}$ and $^{152}\mathrm{Gd}(p,t)^{150}\mathrm{Gd}$ at 30° are shown in Fig. 1. For the reactions $^{160}\mathrm{Gd}(p,t)^{158}\mathrm{Gd}$ and $^{154}\mathrm{Gd}(p,t)^{152}\mathrm{Gd}$, complete angular distributions were taken in 5° steps in the range 5°–80°. Less complete data were obtained on the other targets, but the similarity in the shapes of the angular distributions for a given state allowed the extraction of an integrated yield from 5°–80° in all cases. This is shown in Fig. 2 for the 0^+ and 2^+ states.

As can be seen from Fig. 2, in the three deformed nuclei $^{154-158}\mathrm{Gd}$, only a single excited 0^+ state is relatively strongly populated. These low-lying 0^+ states have earlier been interpreted as β vibrations on the basis of their strong $E2$

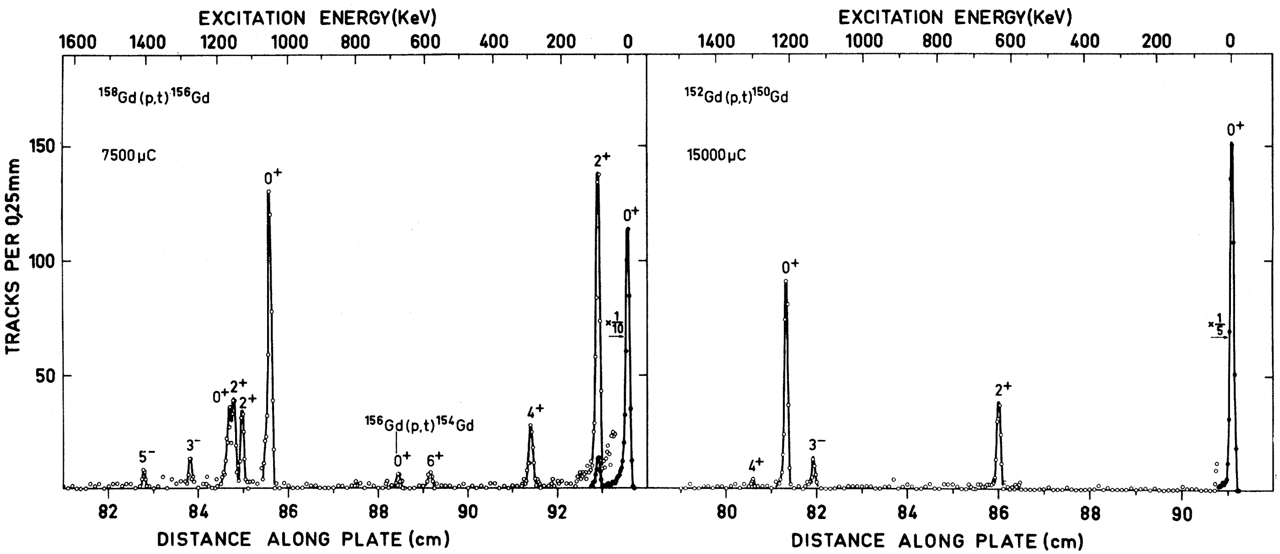

FIG. 1. Energy spectra from the reaction $^{160,152}\mathrm{Gd}(p,t)^{158,150}\mathrm{Gd}$ at 30° and 18 MeV. The energy resolution is about 10 keV.

excitation. Their strength in the (p,t) reaction varies from 12% in ^{156}Gd to 23% in ^{158}Gd, compared to the ground-state strength. This result is consistent with similar observations in the deformed Sm and Nd nuclei[1,2,4] although they cover more restricted mass ranges. A similar consistency in relative cross sections for such low-lying 0^+ states has recently been reported over a wide range of mass in the actinide nuclei.[5] In (p,t) reactions on the Yb nuclei, appreciable strength to excited 0^+ states is seen only in the reaction ^{176}Yb$(p,t)^{174}$Yb.[3]

In ^{152}Gd there is a marked change in that two excited 0^+ states are populated in reaction ^{154}Gd$(p,t)^{152}$Gd (Fig. 2). In particular, the lowest 0^+ state at 615 keV has the same strength as the ground state (g.s.) transition, the latter attaining only one-half the g.s. strength observed in the other Gd nuclei. This is taken as evidence for a phase transition at $N = 88$ between deformed ^{154}Gd and "quasirotational" ^{152}Gd nuclei.[6] This sudden change in deformation results in a poor overlap of the g.s. wave functions and consequently a marked reduction in the cross section for ^{154}Gd$(p,t)^{152}$Gs(g.s.). An analogous observation has been reported in the Sm nuclei.[1,2]

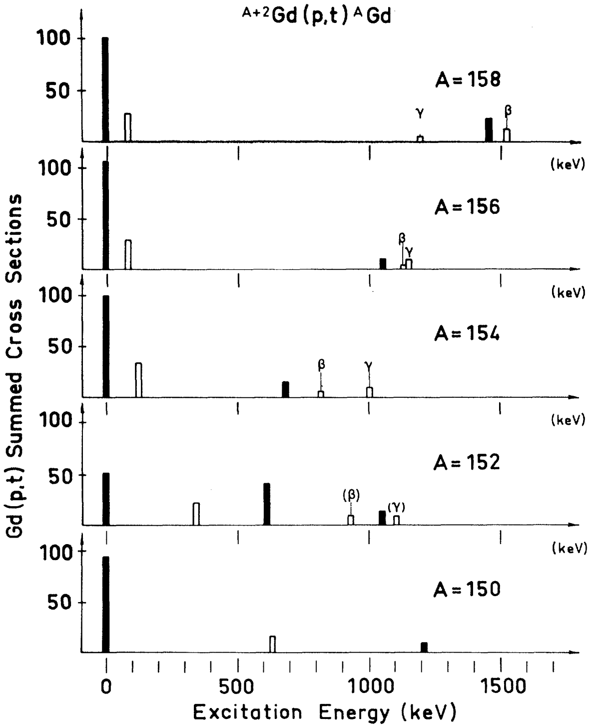

FIG. 2. Summed cross sections for the 0^+ states (solid bars) and 2^+ states (open bars). The relative cross sections between targets obtained in this way are accurate to ±10% for the 0^+ transitions.

With the marked exception of the reaction ^{154}Gd$(p,t)^{152}$Gd, the ground-state to ground-state (p,t) cross sections are constant in all the Gd nuclei, within an experimental error of 10%. As such, they are in poor agreement with the Yoshida prediction of a $(\Delta/G)^2$ dependence,[7] even in a region of constant deformation, where the Yoshida model would be expected to have most validity. Although there is a variation with neutron number, the gap parameters Δ are of order 900 keV[8] and thus the ground states of the Gd nuclei should be largely superconducting. This is reflected in the constancy of the g.s. (p,t) cross sections. Further evidence for the presence of strong pairing correlations is provided by the ground-state configuration $\frac{3}{2}^{-}|521|$ for the odd Gd nuclei from $A = 153$ to $A = 159$. In this respect, the Gd nuclei are somewhat analogous to the highly superconducting Sn nuclei.[9]

No satisfactory theoretical explanations have been given for the observed two-neutron–transfer cross sections leading to excited 0^+ states in deformed nuclei. The lowest 0^+ states are expected to be due to the β-vibrational and pair-vibrational degrees of freedom.[10,11] Other formulations for the existence of 0^+ modes of excitation are also predicted.[12] In a microscopic formalism, the β vibration and pair vibration are constructed from the same two-quasiparticle (qp) basis. Strong mixing can then be expected between these states and, indeed, in the Gd nuclei the lowest 0^+ state is predicted to be essentially an equal mixture of both.[13] The pairing degree of freedom is the natural one to come into play in the two-neutron–transfer reaction, but since the ground states of the Gd nuclei are superconducting, only little (p,t) strength to excited 0^+ states can be expected to arise from fluctuations in the pairing field (pair vibration). Indeed, in (p,t) reactions on the Sn nuclei, no excited 0^+ states are made with more than 4% of the g.s. strength.[9] In the Yb nuclei, the gap parameters are 200 keV smaller than in gadolinium,[8] and measurable (p,t) strength to pair vibrational states may be more likely.[3]

On the deformed Gd nuclei then, the relatively strong population seen of low-lying 0^+ states in the (p,t) reaction is perhaps associated with their β-vibrational character. In most deformed nuclei, the amplitude of zero-point oscillations in the β degree of freedom is small compared to the values of equilibrium deformation, so that in terms of its 2-qp nature, the 0^+ β vibration, in like manner to the pair vibration, should yield a vanishingly small (p,t) cross section. The observed cross sections of $\simeq 15\%$ of the g.s. strength may then provide evidence of the need for including more dynamics in the calculation, such as a β dependence in the two-neutron–transfer operator.[14] However, when the nucleus becomes quasirotational or "soft," the amplitude of the zero-point oscillations become large compared to the equilibrium deformation[15] and the distinction between ground state and 0^+ β vibration becomes much less clear. The dynamic overlap between these two states is then presumably more favorable and results in a much enhanced (p,t) cross section, such as that observed to the 615-keV 0^+ state in ^{152}Gd (Fig. 2), and to the 0^+ "β vibrations" in samarium.[1,2]

The second excited 0^+ state at 1048 keV in the ^{152}Gd spectrum, which is populated with 30% of the g.s. strength in the reaction ^{154}Gd(p,t)-^{152}Gd (Fig. 2), was not observed in the γ-decay work of Ref. 6. Based on its favorable overlap with the ^{154}Gd ground state, this 1048-keV state can be considered to be largely a deformed state "coexisting" in a predominantly spherical nucleus. The analogous case of coexisting 0^+ states exists in the Sm nuclei,[1,2] although in these cases the second 0^+ state is populated much more strongly relative to the ground state than we observe in ^{152}Gd. In Sm, the availability of both (p,t) and (t,p) data has demonstrated that there is very little mixing between the first and second excited 0^+ states and has thus enhanced the credibility of shape coexistence in these nuclei. As yet there are no (t,p) data available on the Gd nuclei.

The reaction ^{152}Gd$(p,t)^{150}$Gd between two predominantly spherical nuclei should yield a very different spectrum from what is observed on a deformed target, as can be seen immediately from Fig. 1. The ^{150}Gd spectrum, with the exception of the 1210-keV level, is in fact very similar to what is observed in 20-MeV (p,t) reactions on the (spherical) tin nuclei.[9] Our angular distribution systematics indicate that the 1210-keV level is 0^+, which is contrary to an earlier[16] 4^+ assignment reported for a level at 1209 keV from the decay of ^{150}Tb. However, a more recent paper on ^{150}Gd places a 4^+ level at 1288 keV,[17] where we also observe a weakly excited state (Fig. 1). This 1210-keV level in ^{150}Gd has 10% of the g.s. strength and is an interesting candidate for a pair vibration in ^{150}Gd since the single-particle energy gap here is of order 1 MeV. A similar strong population of excited 0^+ states has been reported in the spherical Sm nuclei.[1]

Apart from those discussed above, no excited 0^+ states up to 2 MeV excitation are populated with more than 3% of the g.s. strength. In ^{156}Gd, a 0^+ state at 1168 keV[18,19] is observed (Fig. 1). The weak (p,t) cross section for this state would be consistent with its having a neutron pair-vibration structure, but is has also been referred to as a proton pair state.[19] A 0^+ state at 1196 keV observed[20] in ^{157}Gd$(n,\gamma)^{158}$Gd is not seen.

In Fig. 3 are shown typical examples of the angular distribution data for the 0^+ states. The absolute cross sections were determined from a measure of proton elastic scattering and should be accurate to better than 20%. The curves shown are distorted-wave Born-approximation (DWBA) calculations without the inclusion of any channel coupling and assuming a spherical form-factor for all transitions. The calculations have been carried out with code DWUCK, employing the harmonic-oscillator (with Hankel-function matching) prescription of Glendenning.[21] The optical-model parameters were taken directly from Ref. 9.

In the Gd nuclei, the Nilsson single-particle states arise mainly from the $N=5$ oscillator shell, and consequently one can expect the (p,t) form factor to be constructed primarily from such configurations. The DWBA curves given

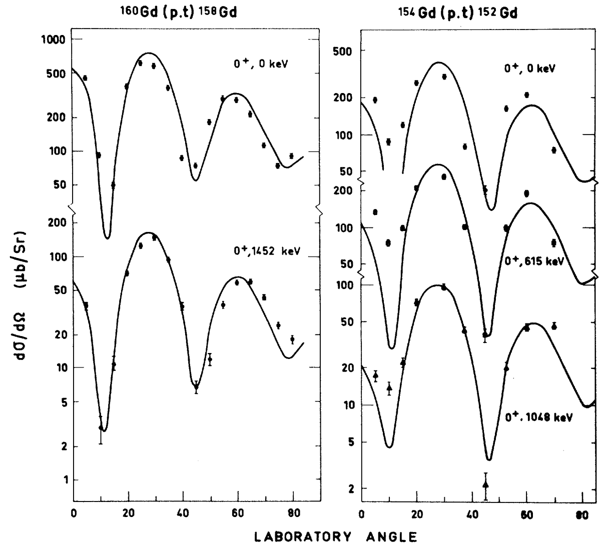

FIG. 3. Angular distributions and DWBA fits for 0^+ states seen in the reaction ^{160,154}Gd$(p,t)^{158,152}$Gd.

in Fig. 3 are based on this assumption. The inclusion of contributions from the $N=6$ shell made little difference on the calculated shapes. The DWBA calculations to the 0^+ transitions are generally good although the shallow first minimum observed in the ground and first excited 0^+ states in the reaction ^{154}Gd$(p,t)^{152}$Gd is not reporoduced by the calculations. On the other hand, the DWBA calculations show a filling in of this minimum with increasing excitation energy. Such a shallow first minimum in the ^{152}Gd 0^+ data is not a feature of the (p,t) $L=0$ transitions in the higher-mass Gd nuclei (cf. Fig. 3). Use of the triton-potential from Jaskola *et al.*,[22] which was chosen to fit the (d,t) g.s. angular distribution on ^{160}Gd, considerably worsened the agreement with the (p,t) data. Other parameter choices were not attempted. It should be noted that in the reaction ^{160}Gd(p,t)-^{158}Gd, the position of the first minimum in the angular distribution to the 1452-keV 0^+ β vibration is shifted inward by about 5° with respect to the g.s. transition, and this shift is qualitatively reproduced by the calculations. A similar shift in the position of the first minimum for (p,t) reactions populating excited 0^+ states has been reported in the actinides.[5]

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Isospin Splitting of the Giant Dipole Resonance, and Muon Capture

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The correspondence between the upper fragment of the split electromagnetic giant dipole resonance and the parent dipole mode excited by muon capture is investigated for nuclei with a neutron excess. Results already found for light $(N=Z)$ nuclei are extended to heavier $(N>Z)$ nuclei, suggesting new types of experiments to demonstrate the isospin origin of this splitting.

There is considerable interest at present in isospin splitting of the electromagnetic giant dipole resonance (gdr) of nuclei with extra neutrons; in such nuclei, two dipole modes with different values of the isospin quantum number are expected to appear in rather well-separated energy regions.[1] Numerous recent photonuclear experiments tend to confirm the reality and the isospin origin of such a splitting.[2] However, none of them, except maybe one,[3] gives a clear-cut indication of the analog character of the upper fragment. On the other hand, considering a nucleus