$T=2$ STATES IN Mg^{24}, Ti^{44}, and Fe^{52}†

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Recent interest in the properties of isobaric analog states[1-4] leads one to consider the possibility of exciting states with isobaric spin $T=T_z+2$. In a nucleus, $B(N,Z)$, these levels are analog of the isobar with $B(N+2,Z-2)$. For example, the $T=2$ levels in Mg^{24} are analogs to the states of Ne^{24} which if charge independence were completely valid would be at exactly the same energy as the $T=2$ levels in Mg^{24}. The Coulomb energy difference, of course, causes them to lie at considerably higher energy in Mg^{24}. In fact these levels lie sufficiently high in energy so that, previously, no two levels in a nucleus have been found that differed by two units of isobaric spin. The γ-ray and/or particle decay of these states should be useful for further exploring the role of isobaric spin in nuclear structure. The fundamental isobaric spin selection rule in γ-ray decay is $\Delta T=\pm 1$, or 0. Interpreting violations of this rule as due to mixing among states of different T makes the decay of these states a sensitive probe for T-spin admixtures.

In a recent paper[5] Garvey and Bayman pointed out that states with $T=T_z+2$ may be reached using two-neutron pickup reactions, i.e., (p,t) or (He^4,He^6). It is pertinent to consider the following reaction with regard to isobaric spin conservation:

$$A(N,Z)[a,b]B(N',Z')$$

In nucleus A, $T_z{}^A$ equals $\frac{1}{2}(N-Z)$ which will usually be the T^A in the ground state. The reaction will populate states in nucleus B with the following isospins:

$$\vec{T}'^B=\vec{T}^A+\vec{T}^a+\vec{T}^b.$$

In a (p,t) reaction on a target with $T^A\geq 1$, levels in nucleus B with $T'^B=T^A+1$, T^A, and T^A-1 may be reached. The ground state of B will have isospin $T^B=T_z{}^B=T^A-1$. The states with $T'^B=T^A+1$ are the ones of interest in this Letter. The analogous transfer reaction that can be used to populate these states is the (He^3,n) reaction.

However, if states differing in T by 2 units from the ground state are to be experimentally observed, considerations other than conservation of isobaric spin must enter. These states will lie at energies where the level density is high, therefore a reaction that enhances their excitation relative to the adjacent levels must be employed. Thus, though the (p,n) reaction satisfies the conditions on the isobaric spin it does not seem very likely that it would be efficient in exciting states with $T=T_z+2$ as simple charge exchange only alters T_z, leaving T unchanged. Calculations within the $1f_{7/2}$ shell where wave functions are now available[6,7] indicate that the (p,t) reaction can selectively populate states with $T=T_z+2$.

The Q values for the excitation of these $T=2$ states induced by (p,t) reactions are typically about 25 MeV for target nuclei from O^{18} to Fe^{54}. The proton beam of the Berkeley 88-in. cyclotron was used in these experiments at an energy of 38.7 MeV. An improved particle identifier designed by Goulding and Landis[8] was used to distinguish the tritons. The energy calibration over the region of interest utilized the $C^{12}(p,t)C^{10}$ reaction to the C^{10} ground and first excited states ($Q=-23.33$ and -26.67 MeV, respectively). The energy resolution was typically 150 keV. Targets of Mg^{26}, Fe^{54}, and Ti^{46} were bombarded in these experiments. The last two were used because calculations[5] showed them to have a large spectroscopic factor for the states of interest.

Figure 1 shows a spectrum obtained for each of the targets at an angle where these $0^+\rightarrow 0^+$, $L=0$ transitions are enhanced. In all cases the differential cross sections of the peaks indicated as $J=0$, $T=2$ paralleled the ground state transition. When the ground state is relatively small, the $J=0$, $T=2$ peaks fall into the background; the Fe^{52} spectra had the highest background due to the beam striking the target holder.

The $0^+\rightarrow 0^+$ (p,t) reactions possess very characteristic[9] angular distributions between 20° and 30° at these energies. They peak at about 25° and fall off quite rapidly, while transitions involving other angular momentum transfers

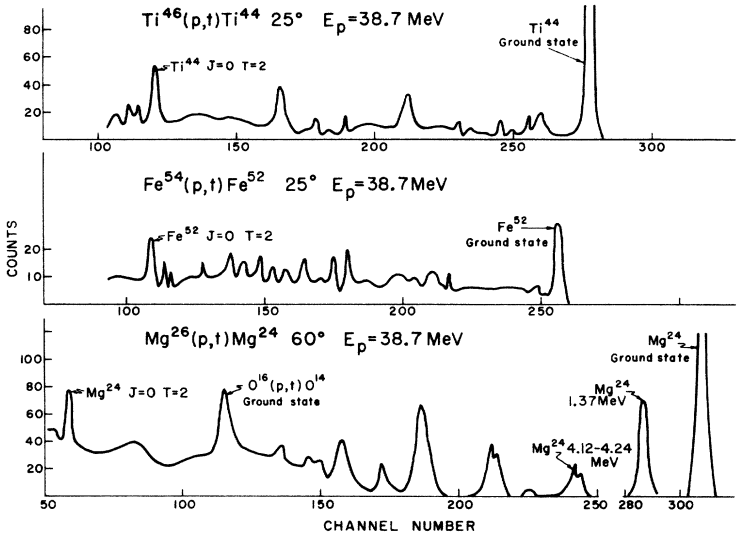

FIG. 1. Energy spectra for the (p,t) reaction on Mg^{26}, Ti^{46}, and Fe^{54} at 38.7 MeV. The states labeled $J=0$, $T=2$ are analogs of the ground state of the corresponding $T=2$ isobar.

vary little over this region. Figure 2 shows the angular variation of the Ti^{44} ground state and state identified as a $T=2$ state; it also presents the $Mg^{26}(p,t)Mg^{24}$ ground state and $T=2$ state angular distributions. [The $L=2$ transition to the Mg^{24}(1.37 MeV) state is included for comparison.] The $L=0$ character of the transitions to the $T=2$ states is apparent. The relative cross sections for the Ti^{44} and Fe^{52} $T=2$ and ground-state transitions qualitatively agree with prediction,[5] but more data and a distorted-wave Born approximation fit to remove the Q dependence are needed before a meaningful comparison can be made.

The excitation energy of these $J=0$, $T=2$ states is determined by adding the Coulomb energy difference minus twice the neutron-proton mass difference to the ground state of the $T_z=2$ member of the isobar. Table I shows the predicted position of the analogs of Ne^{24}, Ca^{44}, and Cr^{52} ground states as found in Mg^{24}, Ti^{44}, and Fe^{52} along with the values obtained in this experiment. The Mg^{24} case was calculated from the 1961 mass tables[10] using the energy difference between the mirror nuclei (Ne^{21}, Na^{21}) and (Na^{23}, Mg^{23}) which is then corrected for the radius difference to get the Coulomb energy. In the case of Ti^{44} and Fe^{52}, recently obtained values[11] for Coulomb energies in this region were used.

Table I also presents the experimental excitation energies of these $T=2$ states. Their errors reflect the 50-keV uncertainty in the C^{10} mass which enters our calibration and the 62 keV/channel required in the analyzer to cover this large range of excitation, coupled with the limited number of observed angles.

Good agreement between the calculated and observed excitation energies of the lowest $T=2$ states of Mg^{24}, Ti^{44}, and Fe^{52} is shown in Table I.

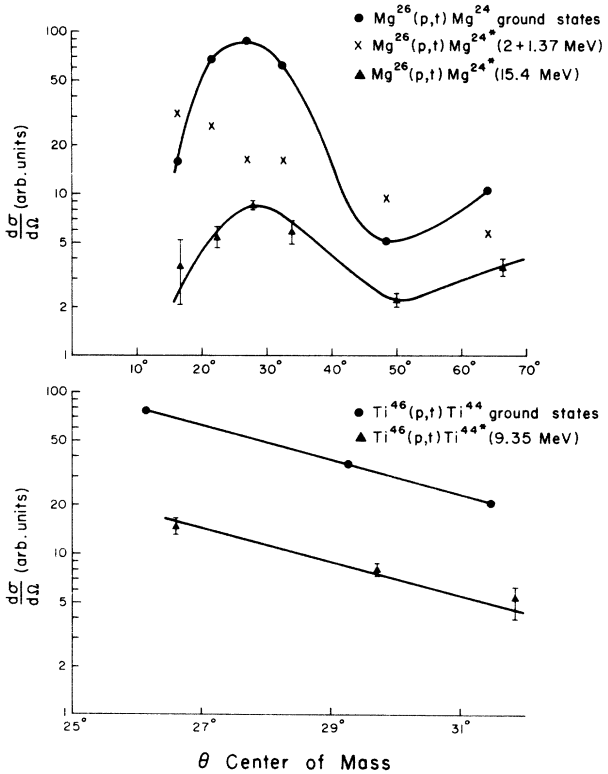

FIG. 2. Top: Angular distributions of the $Mg^{26}(p,t)Mg^{24}$ ground state and 15.4-MeV, $T=2$, state ($L=0$ transfer) and 1.37-MeV state ($L=2$ transfer). Bottom: Variation with angle of the $Ti^{46}(p,t)Ti^{44}$ ground state and 9.31-MeV, $T=2$, state ($L=0$ transfer) cross sections.

Table I. Comparison of the predictions based on Coulomb energies to the experimentally determined excitation energies for the lowest lying $J=0$, $T=2$ levels.

Nucleus	Prediction from Coulomb energy differences (MeV)	Experimental value (MeV)
Mg^{24}	15.30 ± 0.05	15.4 ± 0.12
Ti^{44}	9.44 ± 0.1	9.35 ± 0.12
Fe^{54}	8.46 ± 0.1	8.48 ± 0.12

Further, the states appear sharp with much of the transition strength focused in a small energy interval. Thus it is seen that the (p,t) reaction does pick out states with $T = T_z + 2$ and these states lie near the energies expected from the Coulomb energy difference.

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GEOMETRIC TEST OF THE ISOSPIN MULTIPLET NATURE OF NUCLEAR ANALOG STATES

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Recently, a number of experimental and theoretical studies have appeared bearing on the matter of nuclear states and their isobaric analogs. On the one hand, high-energy electron scattering experiments[1] and their analysis[2] have provided a new probe of the extent to which, say, the fundamental three-body nuclear systems, He^3 and H^3, constitute an isobaric doublet. On the other hand, apparent isobaric analog states have been discovered in fairly heavy nuclei.[3] In this note we propose a possible geometric test of the isospin multiplet nature of a wide variety of nuclear analog states, based upon the following theorem:

Theorem.—Consider the nuclear reaction

$$A + B \rightarrow C + C',$$

where C and C' are members of the same isospin multiplet (isobaric analogs) and where the isobaric spin T of either A or B is zero. If T is strictly conserved, and if C and C' are exactly connected by a rotation in isospace, then the differential cross section of the reaction products will exhibit symmetry about 90 degrees in the center-of-mass system, independently of reaction mechanism. The reaction can be taken as proceeding in either direction.

Proof.—If we think of the system in the isospin formalism, C and C' are identical particles obeying Bose or Fermi statistics, depending upon whether they contain an even or odd number of nucleons. This imposes an overall symmetry condition upon the wave function describing the two particles. Because of the way we have set up the reaction, only one value of T can contribute, so that the product of the space and spin portions of the wave function has definite symmetry. Hence even angular momenta and odd angular momenta are associated with orthogonal spin wave functions which cannot introduce interference terms; the angular distribution will therefore contain only even powers of $\cos\theta$, leading to the conclusion stated above.

As soon as we relax either the condition of strict isospin conservation, or of the strict analog relationship between C and C', symmetry about 90 degrees is no longer required since