# Observation of the Charge-Exchange Mode of the Giant $M1$ Resonance of $^{28}$Si

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The reaction $^{28}$Si$(t, {}^3$He$)^{28}$Al has been performed at a bombarding energy of 23.5 MeV. A number of low-lying $1^+$ states are observed in the spectrum of $^{28}$Al and these are related by the Coulomb energy difference to their analog $1^+$, $T=1$ states which comprise the giant $M1$ resonance structure of $^{28}$Si. Of particular importance, the $(t, {}^3$He) strength distribution to the $1^+$ states in $^{28}$Al largely reproduces the distribution of electromagnetic transition rates of their analogs in Si. This provides strong evidence for the existence of the charge-exchange mode with $\Delta T_z=1$ of the giant $M1$ resonance in $^{28}$Si.

The discovery and excitation of collective modes of the nucleus are among the most important problems in nuclear physics. Of particular interest are the giant resonance modes which are common to all nuclei and are crucial for the understanding of many nuclear phenomena. The most widely studied and best known giant resonance is the electric dipole, but recent emphasis has spread to resonances of other multipolarities[1] and to magnetic as well as electric modes. Most such vibrations possess isovector character and hence are expected to possess several isospin components. The isospin splitting of the giant $E1$ resonance, for example, has been well documented.[2] Another important property of isovector collective vibrations is the supposed existence of charge-exchange components with $\Delta T_z = \pm 1$ and $\Delta T = \pm 1$, but despite theoretical predictions,[3,4] there has been little experimental attention devoted to these important components, and equally little experimental proof of their existence. In addition to providing information about the intrinsic collective vibrations, the charge-exchange modes are uniquely important in certain nuclear processes such as Gamow-Teller $\beta$ decay, and $\mu^-$ capture,[4] as well as in the determination of the isospin-dependent terms in the nuclear force.

The purpose of this Letter is to present experimental evidence for the existence of the charge-exchange mode with $\Delta T_z = +1$ and $\Delta T = +1$ of the $M1$ collective states in the mass-28 isobars and to compare the relative excitation strengths with the electromagnetic excitation of the strong $T_z = 0$, $T=1$, $J^\pi = 1^+$ analogs which comprise the giant $M1$ resonance in $^{28}$Si. The only other experiment to investigate specifically this phenomenon was the recently performed reaction $^{58}$Ni$(t, {}^3$He$)^{58}$Co to study the possible excitation of the charge-exchange mode of the $T_>$ components of the $M1$ strength of $^{58}$Ni.[5] Strong $1^+$ states were observed in $^{58}$Co and from these the position of the $M1$ strength in $^{58}$Ni was inferred using the known Coulomb energy difference. However, the giant $M1$ resonance has not yet been observed in the nickel region by electromagnetic reactions, and hence it is not yet possible to substantiate the existence of charge-exchange modes in this case. To alleviate this difficulty and to evaluate the significance of charge-exchange reactions for exciting collective modes, the present Letter discusses $N=Z$ nuclei where the $T_z=0$, $T=1$ modes of the giant $M1$ strength have been well studied.[6] Of particular importance in certain of these nuclei is the fragmentation of the $M1$ strength into several $1^+$ levels with $T_z=0$ and $T=1$. If the $T_z=\pm 1$ analogs of these states, as excited by the charge-exchange reactions, also show a similar distribution of strength, then the value of such reactions for studying the charge-exchange component of isovector collective modes of the nucleus will be demonstrated.

The present experiment utilized a 23.5-MeV triton beam from the Los Alamos Scientific Laboratory three-stage Van de Graaff facility to bombard an enriched $^{28}$Si target consisting of approximately 100 $\mu$g/cm$^2$ of metal on a 50-$\mu$g/cm$^2$ carbon backing. The $^3$He particles were detected by a counter telescope which consisted of a 50-$\mu$m $\Delta E$ counter and a 2-mm $E$ counter. An on-line computer was used to identify different particles by displaying a plot of $\Delta E$ versus $E$ which was then divided into different particle groups by use of a light pen. The separation between $\alpha$ particles and $^3$He particles was quite adequate even though the $\alpha$-particle intensity was several orders of magnitude greater than the $^3$He intensity. The experimental resolution was 80–100 keV.

The energy spectrum for the $^3$He reaction particles measured at 30° is shown in Fig. 1. The en-

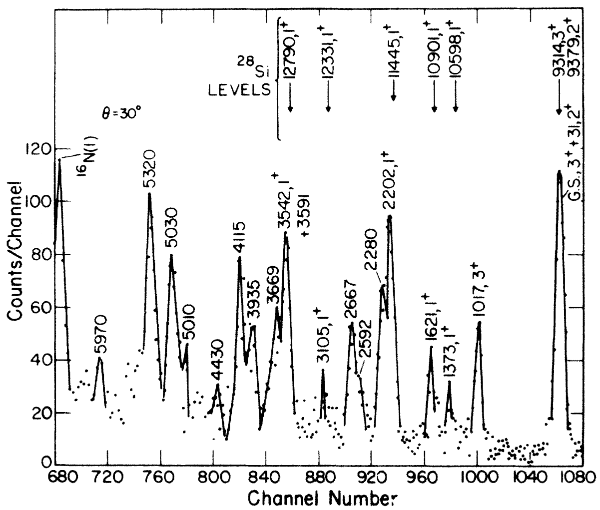


FIG. 1. Spectrum of the reaction $^{28}$Si($t$, $^3$He)$^{28}$Al at $E_t$ = 23.5 MeV. The energies in keV and spin and parity assignments are from the literature as described in the text.

ergy assignments up to 3.5 MeV are made from the known $^{28}$Al level scheme. Above this energy it was not possible to find a reliable correspondence between the energies of the $^3$He groups and the more accurate energy assignments from the literature. The energy assignments were made from the review paper by Endt and Van der Leun,[7] $^{27}$Al($d,p$) results,[8] and $^{26}$Mg($^3$He,$p\gamma$) results.[9] In particular, the data of Ref. 9 identify most of the $1^+$ levels in this region of $^{28}$Al and provide the $1^+$ assignments given in Fig. 1. The average cross section for three angles, 20, 30, and 60°, is given in Table I for each of the four $1^+$ states which are resolved in this experiment. These are at excitation energies of 1373, 1621, 2202, and 3105 keV.

The levels of $^{28}$Al may be related to their analogs in $^{28}$Si by the Coulomb energy difference of 5.467 MeV.[10] The location of five known $T = 1$, $J^\pi = 1^+$ states[11,12] in $^{28}$Si is shown in the upper part of Fig. 1 with arrows indicating the corresponding levels in $^{28}$Al. The observed $M1$ transition rates to the ground state of $^{28}$Si based on electron inelastic scattering experiments are listed in Table I. The reduced transition rates, $B(M1)$, as well as the rates relative to that of the lowest $\Delta T = 1$, $M1$ transition from the 10.598-MeV level are given.

The five $M1$ transitions in $^{28}$Si shown in the table account for 73% of the $M1$ sum rule[11,13] in the $j$-$j$ coupling-scheme limit. On this basis, the $T = 1$, $1^+$ states in the 10.6- to 12.8-MeV $^{28}$Si excitation region constitute the $M1$ giant resonance. The table and figure both indicate that the analogs of at least four of the five components of the $M1$ resonance are excited in $^{28}$Al by the reaction $^{28}$Si($t$, $^3$He). (The fifth component could not be resolved in the $^3$He spectrum.) The main feature to be emphasized in the present data is that the relative ($t$, $^3$He) cross sections for excitation of the $T_z = 1$, $T = 1$, $1^+$ analogs are remarkably similar to the relative $M1$ strengths of the $T_z = 0$, $T = 1$ states as observed in the ($e, e'$) reaction. A similar correspondence in strength was recently reported also for the $A = 24$ isobars based on some preliminary measurements of the reaction $^{24}$Mg($t$,$^3$He).[14] These similarities between the strength distributions of electromagnetic excitation and charge-exchange excitation provide strong evidence for the existence of the isospin modes with $\Delta T_z = \pm 1$ of the collective $M1$ vibration. In addition, the analog relationship between the electromagnetic process and the ($t$,$^3$He)

TABLE I. Excitation energy and strengths for the $M1$ components in $^{28}$Si and their charge-exchange analogs in $^{28}$Al.

| | $^{28}$Si | | | $^{28}$Al | | |
|---|---|---|---|---|---|---|
| Level no. | $E_x$ (MeV) | $B(1^+, E_x)$[a] ($10^{-3}$) | Ratio (to level 1) | $E_x$ (MeV) | $\bar{\sigma}$[c] (mb/sr) | Ratio (to level 1) |
| 1 | 10.598 | 4.3 | 1.0 | 1.373 | 0.017 | 1.0 |
| 2 | 10.901 | 9.5 | 2.2 | 1.621 | 0.035 | 2.1 ± 0.4 |
| 3 | 11.445 | 29.8 | 6.9 | 2.202 | 0.089 | 5.2 ± 1.0 |
| 4 | 12.331 | 8.4 | 2.0 | 3.105 | 0.017 | 1.0 ± 0.2 |
| 5 | 12.790 | 3.4 | 0.8 | b | ... | ... |

[a]From Ref. 11.
[b]Unresolved level.
[c]Average ($t$, $^3$He) cross section at 20, 30, and 60°.

charge-exchange reaction is verified, and a close similarity between the two reaction mechanisms is implied.

The microscopic interaction for a general inelastic excitation may be written

$$v(\vec{r}_i, \vec{r}_p) = \sum_i (V_0 + V_1 \vec{\sigma}_i \cdot \vec{\sigma}_p + V_0' \vec{\tau}_i \cdot \vec{\tau}_p + V_1' \vec{\tau}_i \cdot \vec{\tau}_p \vec{\sigma}_i \cdot \vec{\sigma}_p) g(\vec{r}_{ip}),$$

where the subscripts $i$ and $p$ refer to the target nucleons and projectile respectively, and the sum is over all target nucleons. The quantities $V$ represent the interaction strengths, and the radial dependence of the interaction is contained in the term $g(\vec{r}_{ip})$.

The direct excitation of $1^+$ states with $\Delta T = 1$ by inelastic and charge-exchange processes both occur through the term with strength $V_1'$ since a spin-isospin change is required. This equivalency in interaction strengths has been previously reported for the reactions $^{12}C(^3He, ^3He')$ and $^{12}C(^3He, t)^{12}N$ leading to $T = 1$ analog states.[15] Indeed these authors find the magnitude of $V_1'$ to be the same for the two reactions. This strength relationship also implies that the $M1$ excitation strength of the target nucleus may also be obtained through the $(t, ^3He)$ reaction.

The renewed interest in giant resonance phenomena by many investigators is partially a result of their discovery in the spectra of inelastically scattered particles such as protons, $\alpha$'s, and $^3$He's, whereas previously giant resonances had been associated primarily with electromagnetic processes. The present results suggest that the scope of this subject is much broader than previously conceived, encompassing the use of charge-exchange reactions as well. The results indicate that a systematic study of the charge-exchange modes will add a new dimension to the understanding of collective phenomena in nuclei.

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