Study of Isospin Structure of 1^+ Spin States in ^{58}Ni and ^{58}Cu by the Comparison of ^{58}Ni(p,p') and ^{58}Ni(^{3}He,t)^{58}Cu Reactions

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Abstract. High-resolution measurements of proton inelastic and charge-exchange (^{3}He,t) reactions at 0° on ^{58}Ni were performed. These reactions mainly cause isovector spin flip transitions to M1 states in ^{58}Ni and GT states in ^{58}Cu. The "level-by-level" comparison of analogous M1 and GT transition strengths allows the study of the isospin symmetry structure of highly-excited analog states in ^{58}Ni and ^{58}Cu and identification of isospin T ($T = 1$ and 2) based on the different sensitivities of inelastic and charge exchange reactions.

I ANALOGOUS GT AND M1 TRANSITIONS

A Gamow-Teller (GT) transition is characterized by the quantum numbers $\Delta L = 0$, $\Delta S = 1$ ($J^\pi = 1^+$) and $\Delta T = 1$. GT states are excited favorably in a (^{3}He,t) charge exchange (CE) reaction. The GT final states excited by the (^{3}He,t) reactions on $T_0 = 1$ nucleus ^{58}Ni can have isospin values T_f are 0, 1 and 2.

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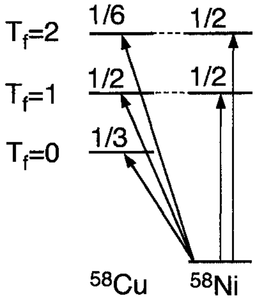

FIGURE 1. The squared isospin CG coefficients of GT and M1 states in ^{58}Cu and ^{58}Ni.

In an inelastic (IE) proton scattering at 0°, 1^+ states can also be excited. These are called M1 states. Only $T_f = 1$ and 2 are allowed for M1 states excited by the ^{58}Ni(p,p') reaction. These M1 states are analogous states of $T_f = 1$ and 2 GT states in ^{58}Cu. Therefore, under the assumption of charge symmetry of nuclear interactions, the excitation energies of 1^+ states with $T_f = 1$ and 2 excited by ^{58}Ni(^{3}He,t) and ^{58}Ni(p,p') reactions should show good correspondence if Q-values and the energy shift from Coulomb interactions are taken into account.

In hadron reactions like (^{3}He,t) and (p,p') at intermediate incident energies and at 0°, there is a good proportionality between the strengths of GT and M1 transitions and cross sections [1,2]. Because of the similarity of hadron CE and IE reactions, the main difference of GT and M1 transition strengths, and thus the difference of cross sections come from different isospin Clebsch-Gordan (CG) coefficients assuming pure $\sigma\tau$ interaction [3].

In Fig 1, the squared CG coefficients of GT and M1 transitions for allowed T_f are shown for the target ^{58}Ni. For the GT and M1 transitions to $T_f = 1$ states, the squared CG coefficients are both 1/2. However, for the transitions to $T_f = 2$ states, they are 1/6 and 1/2 for GT and M1 transitions, respectively. This suggests that in the IE reaction $T_f = 2$ states are three times more favorably excited than in the CE reaction compared with $T_f = 1$ states. Excited states with isospin $T_f = 0$ are observed only in CE reaction. In (n,p)-type CE reaction like (t,^{3}He) and (d,^{2}He) on ^{58} Ni, only 2 is allowed as a T_f value of GT final states in ^{58}Co.

II EXPERIMENTS

Since the isospin symmetry structure of 1^+ states should be studied on a level-by-level base, good energy resolution is needed. This can be realized by the application of *focus* and *lateral dispersion matching* techniques using high resolution magnetic spectrometers. For a large dispersion spectrometer like Grand Raiden, dispersion of the beam line for *lateral dispersion matching* may prevent precise horizontal scattering angle measurement. By applying the *angular dispersion matching* technique,

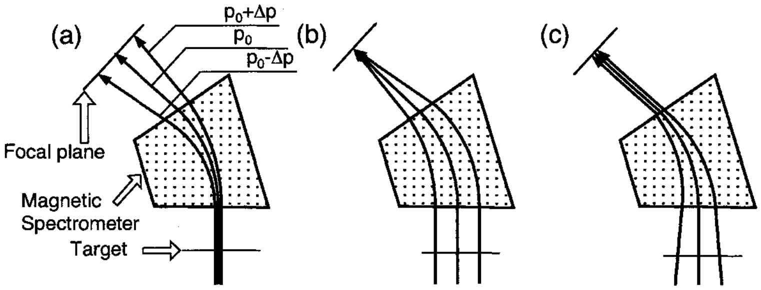

FIGURE 2. Ion trajectories under different matching conditions of a beam line and a magnetic spectrometer. Each of them show the situation (a) when achromatic beam transportation is used; (b) when *lateral dispersion matching* is realized in transporting the beam; (c) when both *lateral dispersion matching* and *angular dispersion matching* are realized. No angle spread of the beam is assumed in the figures so as to show the behaviors of beams with slightly different momentum $\pm\Delta p$ from p_0.

good horizontal angle resolution can be realized. These techniques are illustrated in Fig. 2. Trajectories of the beam with slightly different momenta, p_0 and $p_0 \pm \Delta p$, and assuming no horizontal angle spread in a spectrometer at 0° are shown under the condition that (a) the beam is achromatically transported, (b) *lateral dispersion matching* is realized and (c) both *lateral* and *angular dispersion matchings* are realized.

The 0° ^{58}Ni(p,p') experiment was performed at IUCF by using the K600 spectrometer [4]. The incident proton energy was 160 MeV. In the 0° (p,p') reaction, the incident beam passes through the spectrometer with inelastically scattered particles and is stopped in a special Faraday cup behind the detector system. Therefore, the low excitation energy region cannot be observed and beam halo can cause a large background. The cyclotron and the beam line was tuned to minimize the background from the beam during the experiment. The *lateral dispersion matching* technique was applied [5] and an energy resolution of 35 keV was achieved. As shown in Fig. 3 (a), a low background spectrum was obtained. The excited states at 8.46, 8.60, 8.67, 9.07 and 9.15 MeV are also reported in ^{58}Ni(γ,γ') experiments of F. Bauwens et al. [6] and identified as M1 states.

The ^{58}Ni(^{3}He,t) experiment was performed at RCNP using the Grand Raiden spectrometer and the new beam line WS course at 150 MeV/nucleon. This beam line is designed to realize both *lateral* and *angular dispersion matchings* efficiently [7]. By applying matching techniques, high energy resolution of 50 keV was achieved. In this experiment, the energy spread of the incident beam was estimated to be 250 keV. An energy spectrum of corresponding to the ^{58}Ni(p,p') spectrum is shown in Fig. 3 (b). The fine structure of the GT resonance in the energy region $E_x = 8.5 - 9.5$ MeV was clearly observed.

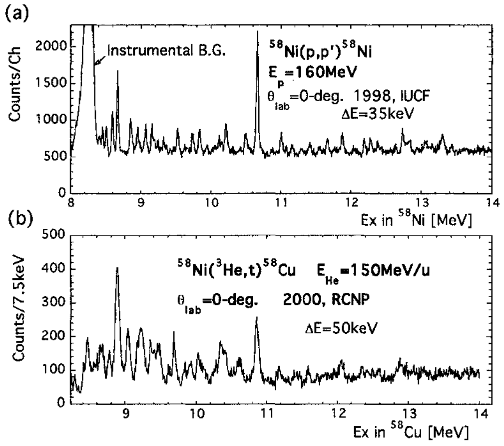

FIGURE 3. Energy spectra from $E_x = 8 \sim 14$ MeV are shown for the ^{58}Ni(p,p') (a) and the ^{58}Ni(^{3}He,t) (b) reaction.

III COMPARISON OF EXPERIMENTAL RESULTS

In an earlier work, isospin distributions of GT states in ^{58}Cu were studied by comparing ^{58}Ni(^{3}He,t) and various other reactions [8]. With the high energy resolution ^{58}Ni(p,p') and ^{58}Ni(^{3}He,t) spectra taken at 0°, more direct and detailed level-by-level comparison of analogous M1 and GT transitions can be performed in order to study the isospin symmetry structure.

From the comparison of ^{58}Ni(p,p') and ^{58}Ni(^{3}He,t) spectra, which are shown in Figs. 3 (a) and (b), correspondence of excitation energies of states is found. For example, the 10.67 MeV state in Fig. 3 (a) corresponds to the 10.85 MeV state in Fig. 3 (b) and the 8.67 MeV state to the 8.88 MeV state. Correspondences of excitation energies suggest that isospin symmetry structure exists even at these high excitation energies and each pair of excited states are analogous GT and M1 states. These analogous GT and M1 states should have isospin values either $T_f = 1$ or 2.

The ratios of events for each pair of analogous states are shown in Fig. 4. For the 10.67 MeV state in ^{58}Ni(p,p') spectrum, which was assigned to be $T_f = 2$ in Ref. [9], the ratio of 3 is given. As discussed above, $T_f = 2$ states are three times more strongly excited in IE reaction than in the CE reaction compared to $T_f = 1$ states. Therefore, the ratios of other $T_f = 2$ states should also be approximately 3, while the ratios for $T_f = 1$ states should nearly be 1.

The calculated ratios are clearly divided into two groups. The group of states in the 8.6 - 10.5 MeV region in (p,p') spectrum show the ratios of about 1. On the other hand, the states above 10.67 MeV show ratios larger than 1, namely about 3. These ratios show good agreement with the predicted values from isospin CG

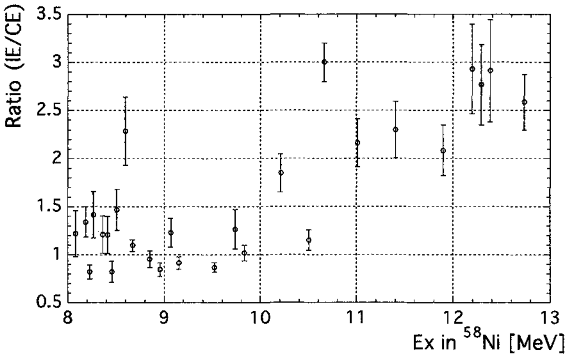

FIGURE 4. Empirical ratios between cross sections of identified analogous states. From the isospin CG coefficients, expected ratios are 1 and 3 for $T_f = 1$ and 2 states, respectively. The horizontal axis shows the excitation energy in (p,p'). Peak fitting was done by software to deduce the number of events of the peaks for each spectrum.

coefficients, which suggests that the states in the first group is of $T_f = 1$ nature and those in the second group is of $T_f = 2$ nature. As expected from isospin symmetry energy, $T_f = 2$ states are found at higher excitation energies compared to $T_f = 1$ states.

It was reported that three states with the excitation energies of 9.83, 10.20 and 10.49 MeV in the (p,p') spectrum were observed in the ^{58}Ni(e,e') experiment [9] and that corresponding analogous states were observed in the ^{58}Ni(t,^{3}He)^{58}Co experiment [10], which suggests these states have $T_f = 2$. In our present analysis these states show the ratios of about 1, suggesting that they are of $T_f = 1$ nature. A possible explanation of these reduced ratios may be the existence of unresolved $T_f = 0$ states near $T_f = 2$ states in the ^{58}Ni(^{3}He,t) spectrum.

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