γ decay from the isobaric analog resonance of $^{63}Ni_{g.s.}$

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The decay widths for the $M1$ and $E2$ transitions in the γ decay of the isobaric analog resonance of the $^{63}Ni_{g.s.}$ have been measured. The preferential excitation of a group of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states in these transitions with $\Delta T=1$ can be directly related to the hindrance of the β decay of $^{63}Ni_{g.s.}$. A detailed comparison with the predictions of the shell model shows the necessity of including excitations from the $1f_{7/2}$ shell in the calculation.

NUCLEAR REACTIONS $^{62}Ni(p,\gamma)$, $E=2.48$ MeV. ^{63}Cu levels measured E_γ and Γ_γ; deduced $B(M1)$ and $B(E2)$. Enriched target, Ge(Li) detector, 3.0 keV at 1.3 MeV. Calculated $B(M1)$ and $B(E2)$. Shell model with Kuo matrix elements.

1. INTRODUCTION

In continuation of the nuclear structure studies of the odd nickel isotopes[1,2] we report here an analysis of the γ decay of the isobaric analog resonance (IAR) corresponding to the $J^\pi=\frac{1}{2}^-$ ground state of ^{63}Ni. The observed transitions are mostly to the $T_<$ states of ^{63}Cu with $J^\pi=\frac{1}{2}^-, \frac{3}{2}^-$, and $\frac{5}{2}^-$. The absolute γ widths have been measured and the $M1$ and $E2$ transition strengths are deduced. A comparison with model predictions is shown to provide new information on the nuclear structure of ^{63}Ni and ^{63}Cu.

A number of theoretical investigations have been carried out for the odd Cu isotopes[3-7] involving the use of the weak or the intermediate coupling models. To the extent that isospin is a good quantum number for the IAR, the collective-model approach to describe them is not useful since these wave functions for the states of ^{63}Cu do not have well defined isospin. Wong[8] has recently carried out shell-model calculations for ^{63}Cu and ^{65}Cu in which the valence nucleons are assumed to occupy the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits. The residual interaction matrix elements of Kuo[9] were used and it is found that the model is successful in predicting the energies of and the transitions among the low-lying $T_<$ states as well as the energies of the isobaric analogue ($T_>$) states. Using these wave functions we have calculated the electromagnetic transition strengths from the $T_>$, $J^\pi=\frac{1}{2}^-$ state to the $T_<$ states of interest.

It is noted that these transitions with $\Delta T=1$ have some special features. For the $M1$ transitions, the spin part of the matrix element is closely related to the β-decay Gamow-Teller (GT) matrix element. This feature is particularly useful in determining the nature of the hindrance factor for β decay in nuclei with a neutron excess, as will be seen later. For the $E2$ transitions, an appreciable enhancement cannot be obtained by invoking effective charge specially for values of $\beta_{proton}\simeq\beta_{neutron}$ as was found to be necessary in this case[8]. To understand the discrepancies between theory and experiment it will be shown that it is essential to include excitations from the $f_{7/2}$ shell.

2. EXPERIMENTAL

Self-supporting targets of isotopically enriched ^{62}Ni (99%) and 40 $\mu g/cm^2$ thick were prepared by electrodeposition. These targets were bombarded with a proton beam from the Université Laval CN Van de Graaff accelerator. The 10-cm-diam. stainless steel target chamber constructed for this work permited us to study simultaneously the γ rays produced in the (p,γ) reaction and the protons scattered at 167° lab. The proton excitation function at 167° lab enabled us to identify the IAR of interest in an unambiguous manner.

The γ rays were detected by a 50-cm³ Ge(Li) detector which had a resolution of 3 keV full width at half maximum (FWHM) for 1.3-MeV γ rays and of 8 keV for 9-MeV γ rays. The γ-ray excitation function was obtained by setting a threshold at $E_\gamma=6$ MeV and summing over all the events above this threshold where each point was measured for a comparatively small amount of charge of 50 μC. The excitation function was determined in steps of 2 keV which was also the over-all resolution of the system in the present experiment. For the angular distributions, a second 30-cm³ Ge(Li) detector mounted at 90° to the beam direction was used as a monitor.

To obtain the absolute widths of the transitions, the efficiency curve of the Ge(Li) detector was constructed, using the γ rays from the $^{26}Mg(p,\gamma)$ reaction and calibrated γ-ray sources of ^{56}Co and

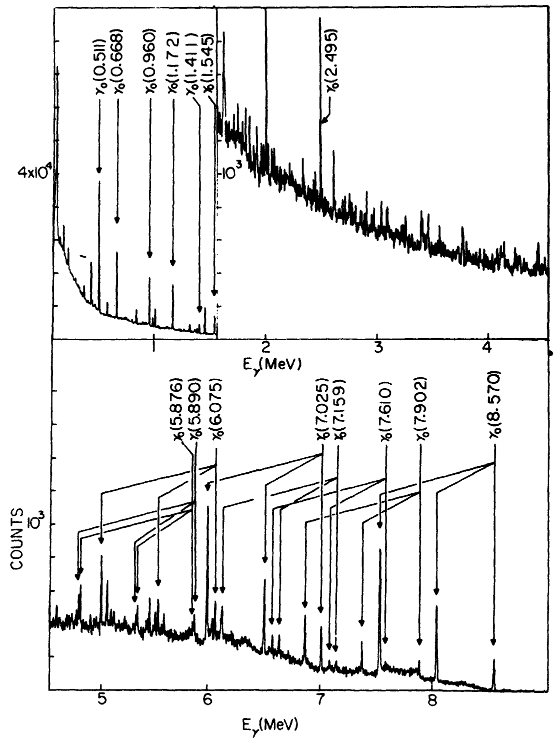

FIG. 1. A spectrum taken with the Ge(Li) detector showing some of the transitions observed in the decay of the IAR in ^{63}Cu.

^{60}Co mounted in the same geometry with respect to the detector as the target in the (p,γ) experiment. The branching ratios and the angular distributions of ^{26}Mg(p,γ) reaction were taken from Ref. 10. The detector efficiency calibration was checked at two different γ energies. The absolute yield of the 1.172-MeV γ ray from the $(p,p'\gamma)$ reaction leading to the first excited state of the target nucleus was found to agree within the experimental errors, with the inelastic proton cross section measured at the same proton energy. At the other end of the scale, for γ-ray energies of around 7.3 MeV we measured the transition strengths from the $\frac{9}{2}^+$ analog resonances to the $\frac{9}{2}^+$ antianalog state of ^{63}Cu at 2.509 MeV for E_p between 3.7 and 3.8 MeV. The $B(M1)$ values that were obtained were found to agree within the quoted errors with the values of Ref. 11.

3. RESULTS

The analog resonance corresponding to the $\frac{1}{2}^-$g.s. of ^{63}Ni was observed both in the elastic proton and the γ-ray channel. A γ spectrum was then obtained for an accumulated charge of 20 000 μC at the resonance energy, a part of which is shown in Fig. 1. The γ-ray energy calibration was obtained in part by using sources and in part by using the known background lines in the spectra. The

TABLE I. The values of $B(M1)$ and $B(E2)$ deduced from the measured Γ_γ for the transitions from the ^{63}Ni$_{g.s.}$ IAR in ^{63}Cu to the low-lying states of ^{63}Cu (column 1). The values predicted by the shell model are given in columns 9 and 10.

E_{ex} (MeV) ±2 keV	E_{ex} (MeV) Ref. 15	E_{ex} (MeV) Ref. 20	J^π	Γ_γ (eV)	Assumed multipole order	Experiment B_{M1} $(\mu_N^2)\times10^{-2}$	Experiment B_{E2} $(e^2$ fm$^4)$	Theory B_{M1} $(\mu_N^2)\times10^{-2}$	Theory B_{E2} $(e^2$ fm$^4)$
0	0	0	$\frac{3}{2}^-$	0.203 ±0.055	$E2$		5.4	11.8	0.4
0.668	0.6696	0.67	$\frac{1}{2}^-$	0.054 ±0.028	$M1$	0.93		0.24	
0.960	0.9619	0.96	$\frac{5}{2}^-$	0.023 ±0.009	$E2$		1.1		0.2
1.411	1.4119	1.41	$\frac{5}{2}^-$	0.031 ±0.010	$E2$		2.0		1.2
1.545	1.5469	⋯	$(\frac{1}{2}^-,\frac{3}{2}^-)$	0.297 ±0.040	$E2$		22.0	1.6	0.08
2.060	2.0620	2.06	$(\frac{1}{2}^-,\frac{3}{2}^-)$	0.081 ±0.015	$M1$	2.5			
2.495	2.4977	⋯	$\frac{3}{2}^-$	0.146 ±0.020	$M1$	5.5			
2.680	⋯	2.69	$(\frac{1}{2}^-,\frac{3}{2}^-)$	0.061 ±0.020	$M1$	2.5			
2.694	2.6967	2.78	$(\frac{1}{2}^-,\frac{3}{2}^-)$	0.045 ±0.020	$M1$	1.9			
3.098	3.1009	2.88	$(\frac{1}{2}^-,\frac{3}{2}^-)$	0.046 ±0.023	$M1$	2.4			
3.427	⋯	3.43	$(\frac{1}{2}^-,\frac{3}{2}^-)$	0.036 ±0.020	$M1$	2.2			

γ-ray energy for the transition from the $T_>$, $J^\pi = \frac{1}{2}^-$ IAR to the $T_<$, $J^\pi = \frac{3}{2}^-$g.s. of ^{63}Cu was determined to be 8.570 MeV which yielded $\Delta E_c = 9.287 \pm 0.003$ MeV, in good agreement with earlier determinations.[12,13] The energies of the γ rays for the transitions in ^{63}Cu observed in the present experiment together with their values obtained in the (^{3}He, d) reaction[14] and in the β decay[15] of ^{63}Zn are found to be in good agreement. Table I lists only those transitions which could be traced to the ground state of ^{63}Cu.

For the transition from the $J^\pi = \frac{1}{2}^-$, $T_>$ to the $J^\pi = T_<$ ground state of ^{63}Cu it is not possible to determine the $M1$ and $E2$ contributions because of the isotropic γ-ray angular distribution. The ^{63}Ni ground state decays by β emission entirely to the ground state of ^{63}Cu with a logft value of 6.8 corresponding to a value of 0.004 eV for the width. If one makes the assumption[16] that the $M1$ matrix element for the γ decay is equal to that for the GT β decay to within a few percent, one can conclude that this transition is almost entirely $E2$ in character. The transition to the first excited $\frac{1}{2}^-$ state at 0.668 MeV is a pure $M1$ while the transitions to the $\frac{5}{2}^-$ states at 0.960 and 1.411 MeV are entirely $E2$ in character (Table I).

4. $M1$ TRANSITIONS

We now compare the experimental values with the model predictions obtained by using the Wong wave functions[8] and the code TENSOR.[17] For the transition to the ground state of ^{63}Cu, the value of the double-barred matrix element[17] (DBME) for the β decay was found to be -2.74 which was very close to the DBME value of -2.56 for the $M1$ transition. For the β decay, the experimental value for the transition strength is a factor of 360 less than the calculated value. Such hindered transitions in medium and heavy nuclei have been discussed in relation to the sum rule for β decay.[18] It has been suggested that part of the total strength would be in the energetically forbidden transitions to states of the Gamow-Teller giant resonance. In the particle-hole picture, spin-flip ($\bar{n}$-p) states of ^{62}Cu are generated by operating with the Gamow-Teller operator $\sum_j \tau_{j-}\sigma_j$ on the ground state of ^{62}Ni; the energies and the distribution of these states referred to as the GT giant resonance [18] depend on the spin- and the isospin-dependent residual interactions. In the case of ^{62}Cu, these states would be of the type $[(\pi f_{5/2})(\nu f_{7/2})^{-1}]_{1^+}$ which have not been taken into account in the present shell-model calculation. The states of the GT giant resonance in ^{63}Cu are obtained by weak coupling the j of the extra nucleon to the 1^+ core states and are basically collective in character.

From the value of ΔE_c and the difference in the binding energy between a neutron in ^{62}Ni and a proton in ^{62}Cu, the unperturbed energy[19] of the spin-flip state below the analog state is calculated to be 4.7 MeV. This, together with the fact that the shell model satisfactorily accounts for states of up to 2 MeV excitation[8] would indicate that the GT states in ^{63}Cu would be above 2-MeV excitation energy. States have been observed in the (^{3}He, d) reaction[14,20] on ^{62}Ni and the (t, α) reaction[21] on ^{64}Zn with $l = 1$ between 2 and 4 MeV excitation in ^{63}Cu. An analysis of the γ spectra revealed several such states preferentially excited in the decay of the $J^\pi = \frac{1}{2}^-$ IAR (Table I). The spin assignments are taken from the earlier work[14,15,20,21] except for the state at 2.495 MeV. The angular distribution of the γ ray from this state to the ground state of ^{63}Cu is anisotropic and would eanble us to assign $J^\pi = \frac{3}{2}^-$ excluding the $\frac{1}{2}^-$ possibility. The γ transitions to the states of $\frac{3}{2}^-$ would be magnetic dipole and electric quadrupole, but entirely dipole to the $\frac{1}{2}^-$ states. To make an estimate, assuming that all these transitions are $M1$ in character, we obtain a value of $0.17\mu_N^2$ for $\Sigma B(M1)$ to these states (Fig. 2) which could be taken as an approximate measure[19] of the unhindered β-decay strength of ^{63}Ni.

For the transition to the $\frac{1}{2}^-$ first excited state of ^{63}Cu at 0.668 MeV, we find that the experimental value for the $B(M1)$ is $0.009\mu_N^2$; the calculated value is $0.002\mu_N^2$ which is indeed small in comparison with that predicted for the transition to the ground state. The dominant component in the wave function describing the $\frac{1}{2}^- T_>$ state is $[(f_{5/2})_0^2(p_{3/2})_0^4(p_{1/2})]_{1/2}$ with an amplitude of 0.95. For the $\frac{1}{2}^-$ first excited state the corresponding configuration is $[(\nu f_{5/2})_0^2(\nu p_{3/2})_0^2(\pi p_{1/2})]_{1/2}$ which has the largest amplitude of 0.51 in the wave function. This state then has the characteristic in part of

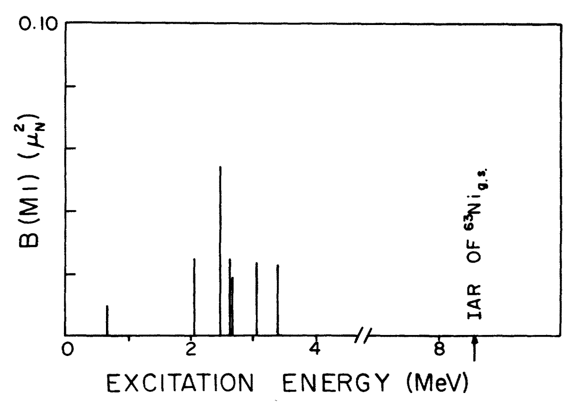

FIG. 2. The strength of the assumed magnetic dipole transitions (Table I) plotted as a function of the excitation energy of the final states in ^{63}Cu.

an antianalog to the $\frac{1}{2}^- T_>$ state. With the core particles coupled to zero, the strength of the transitions between $T_>$ and $T_<$ states with initial and final spins of $J=j=l-\frac{1}{2}$ is reduced[22] by a factor of between 20 and 200 in comparison with that between states of $J=j=l+\frac{1}{2}$. The observed value for $B(M1)$ is in accord with the theoretical prediction, confirming the validity of the above arguments.

5. E2 TRANSITIONS

From Table I we find that the experimental $B(E2)$ value to the first $\frac{5}{2}^-$ state at 0.960 MeV is smaller than that to the second $\frac{5}{2}^-$ state at 1.411 MeV. The model calculation reproduces this feature but the predicted value for the first $\frac{5}{2}^-$ state is 5 times smaller than the observed value, whereas for the second $\frac{5}{2}^-$ state it is about $\frac{1}{2}$ of the experimental value. Considering the transitions to the $\frac{3}{2}^-$ states, if we assume that the transition to the ground state is almost entirely $B(E2)$, the experimental value is an order of magnitude larger than the predicted value. Lastly, a strong transition is observed to the 1.545-MeV state (Fig. 1). It has been found that this state is strongly excited in the inelastic scattering[23] of protons on ^{63}Cu, but weakly excited in the ^{62}Ni(τ, d) reaction[14,20]. In the ^{64}Zn(t, α) reaction,[21] the angular distribution of this state is characterized by $l=1$ thus restricting its spin to $\frac{1}{2}^-$ and $\frac{3}{2}^-$. An assignment of $J^\pi=\frac{3}{2}^-$ is favored for this state from a recent angular-correlation study[24] of the ^{60}Ni($\alpha, p\gamma$) reaction. According to the shell model[8] this level is like a single particle with an appreciable stripping strength in the proton transfer reaction, whereas the weak coupling model[7] would characterize this as a one-phonon $\frac{3}{2}^-$ state. The experimental evidence would favor the latter interpretation and in view of the collective nature of this state, the transition in the present experiment could be assumed to be largely $E2$. In summary, the shell model qualitatively agrees with experiment, but fails to account for the larger $B(E2)$ values observed in the transition to the $\frac{5}{2}^-$ and $\frac{3}{2}^-$ states (Table I).

The operators for electromagnetic transitions among the low-lying $T_<$ states can be written as a sum of the $\Delta T=0$ and the $\Delta T=1$ terms. For these transitions it was found[8] that an effective charge of $2.5e$ for protons and $1.5e$ for neutrons would sufficiently enhance the $B(E2)$ values and bring them in line with the observed values. In the present case, the electric quadrupole operator for transitions between $T_>$ and $T_<$ states has only the $\Delta T=1$ term and is proportional to the sum of the single particle operators:

$$-\frac{e}{2}[1+(\beta_p-\beta_n)]\tau_3 r^2 Y_2 .$$

It is clear that an effective charge with $\beta_p=\beta_n$ would leave the value of $B(E2)$ unchanged.

A renormalization of the charge would involve excitations of particles from the $f_{7/2}$ shell which has been neglected in the present shell-model calculation. As is evident from previous studies of nuclei in this region, configurations involving the $f_{7/2}$ shell are very important[25] in weak and electromagnetic processes though they have only a small effect on the energies of the low-lying states. The assumption of equality of β_p and β_n is based on the symmetry between protons and neutrons which can be excited from this shell. Actually because of the neutron excess in these nuclei, this symmetry is broken and as a consequence the effective charges no longer cancel each other in the $\Delta T=1$ transitions and an enhancement may still be possible.[26]

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