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AN IMPROVED SCHEME FOR THE DECAY OF 86 sec ^{61}Zn

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Abstract: The levels in ^{61}Cu populated in the decay of 86 sec ^{61}Zn have been reinvestigated using a 29 cm^3 Ge(Li) detector in an anti-Compton arrangement which employed a large NaI(Tl) annular detector. From extensive γ-ray energy and intensity measurements as a function of time ten new γ-rays were assigned to ^{61}Zn decay and levels at 475.0, 970.3, 1311.0, 1394.6, 1660.5, 1904.5, 1932.5, 2088.8, 2204.3, 2358.2, 2472.6, 2684.0, 2793.0, 2840.6, 2857.0, 2933.3, 3019.2, 3092.3 and 3521.1 keV were observed to be populated in the decay of ^{61}Zn. From log ft values determined in this work, from γ-ray intensity information, and from previously reported correlation data from nuclear reactions definite J^{π} assignments have been made for six levels and limits have been placed for another six levels in ^{61}Cu.

E | RADIOACTIVITY ^{61}Zn [from ^{58}Ni(^{4}He, n)]; measured E_{γ}, I_{γ}; deduced log ft. ^{61}Cu deduced levels, J, π. Enriched ^{58}Ni targets; Ge(Li)–NaI(Tl) anti-Compton spectrometer.

1. Introduction

The decay of ^{61}Zn was recently investigated by Hoffman and Sarantites [1]) by means of high-resolution Ge(Li) detectors via singles and $\gamma\gamma$ coincidence measurements who reported levels at 476.3, 970.7, 1311.1, 1664.4, 1908.1, 2090.9, 2359.2, 2474.3, 2684.7, 2743.7, 2841.5 and 2932.7 keV in ^{61}Cu populated in the decay of ^{61}Zn. The levels of ^{61}Cu have been recently studied via a variety of nuclear reactions. Here we mention the triple correlations in ^{60}Ni(p, $\gamma\gamma$)^{61}Cu by Gossett and August [2]); the ^{60}Ni(^{3}He, d) reaction study by Pullen and Rosner [3]); the ^{64}Zn(p, ^{4}He) study of Brown *et al.* [4]); the ^{60}Ni(d, n) work of Fuchs *et al.* [5]), of Okorokov *et al.* [6]) and of Marusak [7]); and the high-resolution ^{58}Ni(^{4}He, p) work of Hoffman and Sarantites [8]).

The reinvestigation of the decay of 86 sec ^{61}Zn was undertaken because it was believed that with the use of higher efficiency and higher-resolution Ge(Li) detectors in conjunction with a large anti-Compton NaI(Tl) annular detector a substantial improvement in the energy and intensity of the γ-transitions in ^{61}Cu could be obtained. This information is also essential for comparison with the branching ratios determined from a recent ^{58}Ni(^{4}He, pγ) reaction study [8]). From the present work ten new γ-transitions have been assigned to the decay of ^{61}Zn and two additional levels in ^{61}Cu have been shown to be populated in the ^{61}Zn decay.

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2. Experimental procedures

The ^{61}Zn radioactivity was produced by the (^{4}He, n) reaction using a 15 MeV ^{4}He ion beam from the cyclotron at Washington University. The targets were double 1 mg/cm^2 foils of Ni highly enriched in mass 58. The targets were bombarded for a period of 100 sec in a small scattering chamber, this was then followed by obtaining spectra for two consecutive time intervals of 100 and 200 sec. This procedure was repeated many times by proper programming of (i) the low level rf power supply of

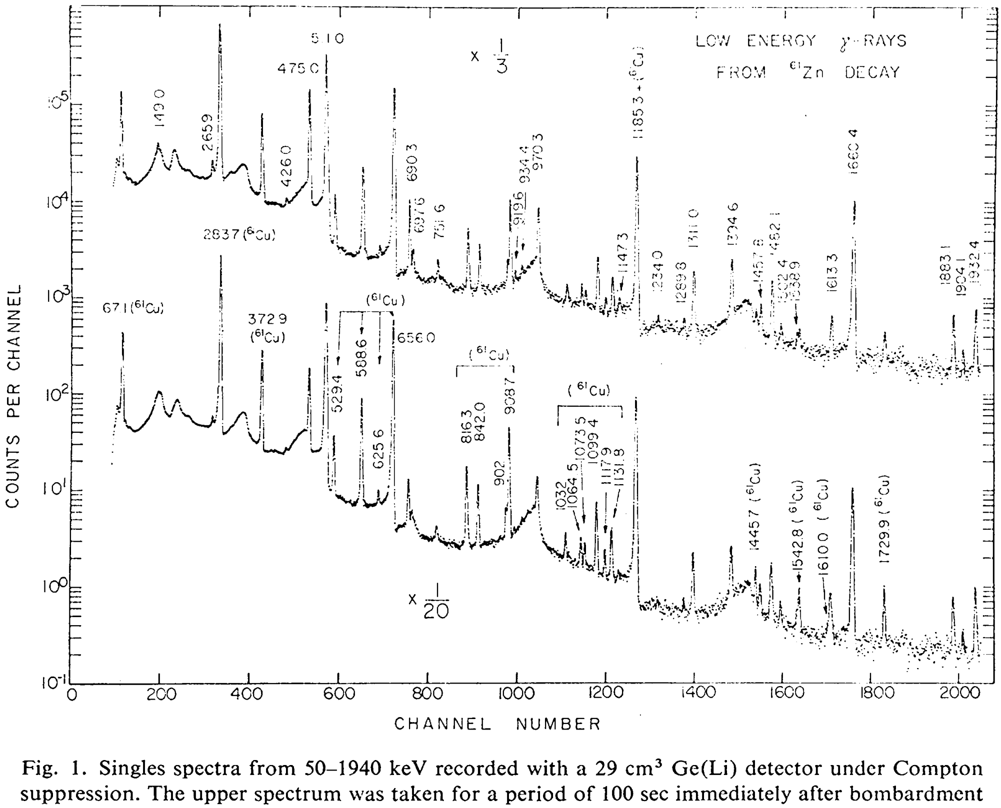

Fig. 1. Singles spectra from 50–1940 keV recorded with a 29 cm^3 Ge(Li) detector under Compton suppression. The upper spectrum was taken for a period of 100 sec immediately after bombardment and labels the γ-rays following ^{61}Zn decay. The lower spectrum was taken for a period of 200 sec after the measurement of the upper spectrum was completed and labels the γ-rays from the decay of the daughter 3.4 h ^{61}Cu. These spectra were accumulated for ≈ 100 cycles.

the cyclotron, (ii) an electrically driven mechanical beam shutting gate and (iii) the on and off position switch of the pulse-height analyser. The two spectra taken at consecutive times from the repeated runs were accumulated in the two halves of the memory of a 4096-channel pulse-height analyser. With this procedure spectra could be accumulated for a period of 8-10 h.

For γ-ray counting, use was made of a 29 cm^3 Ge(Li) in an anti-Compton arrangement with an annular NaI(Tl) detector (length 12.7 cm, outer diameter 19.1 cm and inner diameter 6.5 cm). This detection system and its calibration has been described in some detail elsewhere [9]). The energies of the most intense higher-energy γ-rays were determined from spectra recorded simultaneously with a ^{56}Co standard source. The peak positions were determined by fits to a Gaussian shape by least-squares techniques. To correct for a small non-linearity of the detection system the peak position as a function of energy was fitted to a cubic equation.

The relative intensities of the γ-rays were determined from peaks areas as described in ref. [9]).

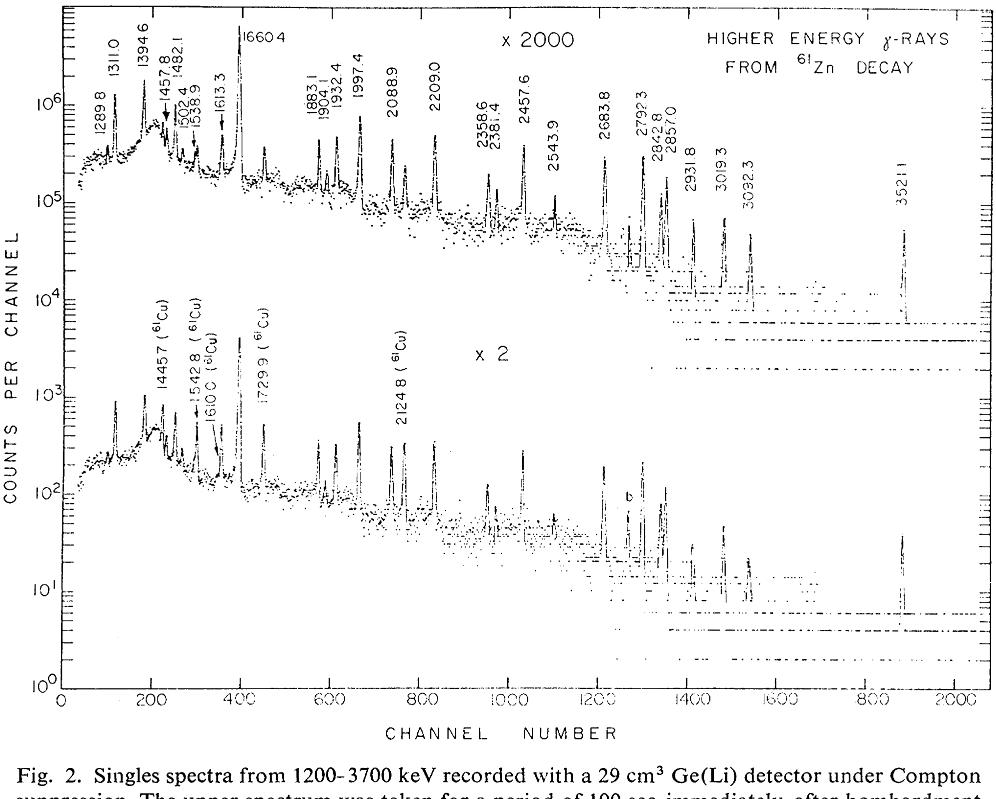

Fig. 2. Singles spectra from 1200–3700 keV recorded with a 29 cm^3 Ge(Li) detector under Compton suppression. The upper spectrum was taken for a period of 100 sec immediately after bombardment and labels the γ-rays following ^{61}Zn decay. The lower spectrum was taken for a period of 200 sec after the measurement of the upper spectrum was completed and labels the γ-rays from the decay of the daughter 3.4 h ^{61}Cu and the background long-lived radiations (b).

3. Results and discussion

Typical spectra of the lower-energy γ-rays recorded for two consecutive 100 and 200 sec intervals are shown in figs. 1a and b, respectively. The higher-energy portion of the same spectra is shown in figs. 2a and b.

The energy and intensity of the γ-rays from ^{61}Zn are summarized in table 1. The first column of table 1 gives the transition between the numbered levels in ^{61}Cu that

TABLE 1

Energy and intensity of γ-rays following 86 sec ^{61}Zn decay from singles measurements

Transitions [a])	E_γ(keV) this work [b])	E_γ(keV) from scheme [c])	E_γ(keV) from ref. [1])	I_γ this work [b])	I_γ from ref. [1])
	149.0 *3*			2.2 *9*	
5 → 4	265.9 *1*	265.9 *1*(4)	267.7 *3*	7.0 *4*	6.7 *7*
10 → 7	426.0 *4*	426.7 *3*(4)		1.9 *1*	
1 → 0	475.0 *1*	475.0 *1*(1)	476.30 *15*	216 *3*	211 *15*
5 → 2	690.3 *1*	690.2 *1*(4)	690.9 *8*	24.0 *18*	21.6 *22*
10 → 5	697.6 *1*	697.7 *2*(4)		5.5 *5*	
14 → 8	751.6 *1*	751.8 *3*(2)	750.7 *11*	4.0 *5*	5.8 *17*
4 → 2	919.6 *3*	919.6 *3*(1)		1.2 *2*	
6 → 2	934.4 *3*	934.2 *2*(2)	936.4 *20*	1.1 *5*	0.9 *5*
2 → 0	970.3 *1*	970.3 *1*(1)	970.70 *13*	39.6 *14*	36.9 *18*
	1147.3 *3*			2.0 *3*	
5 → 1	1185.3 *3*	1185.5 *1*(4)	1185.1 *3*	22.1 *14*	21.7 *15*
9 → 2	1234.0 *4*	1234.0 *4*(1)		1.2 *4*	
12 → 4	1289.8 *6*	1289.4 *4*(3)		1.12 *11*	
3 → 0	1311.0 *1*	1311.0 *1*(1)	1311.1 *6*	12.0 *2*	8.9 *5*
4 → 0	1394.6 *1*	1394.6 *1*(1)	1394.9 *6*	15.6 *4*	16.4 *17*
7 → 1	1457.8 *1*	1457.5 *2*(2)	1459.6 *5*	3.2 *2*	4.4 *12*
13 → 3	1482.1 *1*	1482.0 *2*(2)	1483.0 *4*	10.1 *3*	9.5 *5*
11 → 2	1502.4 *1*	1502.3 *2*(2)	1504.9 *20*	1.8 *2*	2.4 *5*
16 → 4	1538.9 *2*	1538.7 *3*(3)		1.09 *10*	
8 → 1	1613.3 *2*	1613.8 *2*(2)	1614.9 *5*	3.8 *3*	3.8 *8*
5 → 0	1660.4 *1*	1660.5 *1*(4)	1661.3 *9*	100.0 *23*	100.0
10 → 1	1883.1 *3*	1883.2 *2*(4)	1884.0 *9*	6.15 *12*	3.8 *11*
6 → 0	1904.1 *9*	1904.5 *2*(2)		1.17 *16*	
7 → 0	1932.4 *1*	1932.5 *2*(2)	1933.7 *5*	8.5 *5*	6.2 *9*
11 → 2	1997.4 *2*	1997.6 *2*(2)	1997.7 *9*	15.1 *4*	16.0 *9*
8 → 0	2088.9 *1*	2088.8 *2*(2)	2089.9 *10*	8.05 *13*	9.1 *6*
12 → 1	2209.0 *2*	2209.0 *4*(3)	2209.2 *8*	10.8 *6*	11.6 *7*
10 → 0	2358.6 *3*	2358.2 *2*(2)	2358.6 *10*	4.2 *3*	3.5 *4*
15 → 1	2381.4 *20*	2382.0 *4*(2)	2382.1 *20*	1.4 *2*	1.1 *2*
16 → 1	2457.6 *4*	2458.3 *3*(3)	2457.2 *13*	8.4 *5*	10.0 *10*
17 → 1	2543.9 *30*	2544.2 *11*(2)		0.97 *18*	
12 → 0	2683.3 *6*	2684.0 *4*(3)	2683.4 *10*	8.7 *6*	8.5 *9*
13 → 0	2792.3 *3*	2793.0 *2*(2)	2792.6 *14*	10.3 *3*	10.0 *10*
14 → 0	2842.8 *6*	2840.6 *3*(2)	2841.5 *3*	3.18 *3*	3.4 *6*
15 → 0	2857.0 *3*	2857.0 *4*(2)	2856.5 *11*	5.5 *8*	4.5 *6*
16 → 0	2931.8 *3*	2933.3 *30*(3)	2931.6 *20*	1.2 *3*	1.4 *4*
17 → 0	3019.3 *11*	3019.2 *11*(2)	3016.8 *27*	2.4 *3*	2.6 *3*
18 → 0	3092.3 *13*	3092.3 *13*(1)	3090.5 *15*	1.5 *3*	2.2 *6*
19 → 0	3521.1 *15*	3521.1 *15*(1)		1.8 *4*	

[a]) Levels connected by the transitions indicated are numbered as indicated in table 2.

[b]) Results obtained as the weighted averages from four spectra.

[c]) This is the transition energy deduced from the ^{61}Cu level energies given in table 2. The level energies are weighted averages of energy sums, the number of which is given in parentheses for the deexciting level.

are populated in the decay of ^{61}Zn. The second and fifth columns in table 1 give the γ-ray energies and intensities determined in the present experiments. The third column in table 1 gives the transition energies as obtained from the level energies given for the proposed scheme which in turn were determined as weighted averages of energy sums leading to each level. Columns four and six of table 1 give, for comparison, the energies and intensities of the γ-rays from ref. [1]).

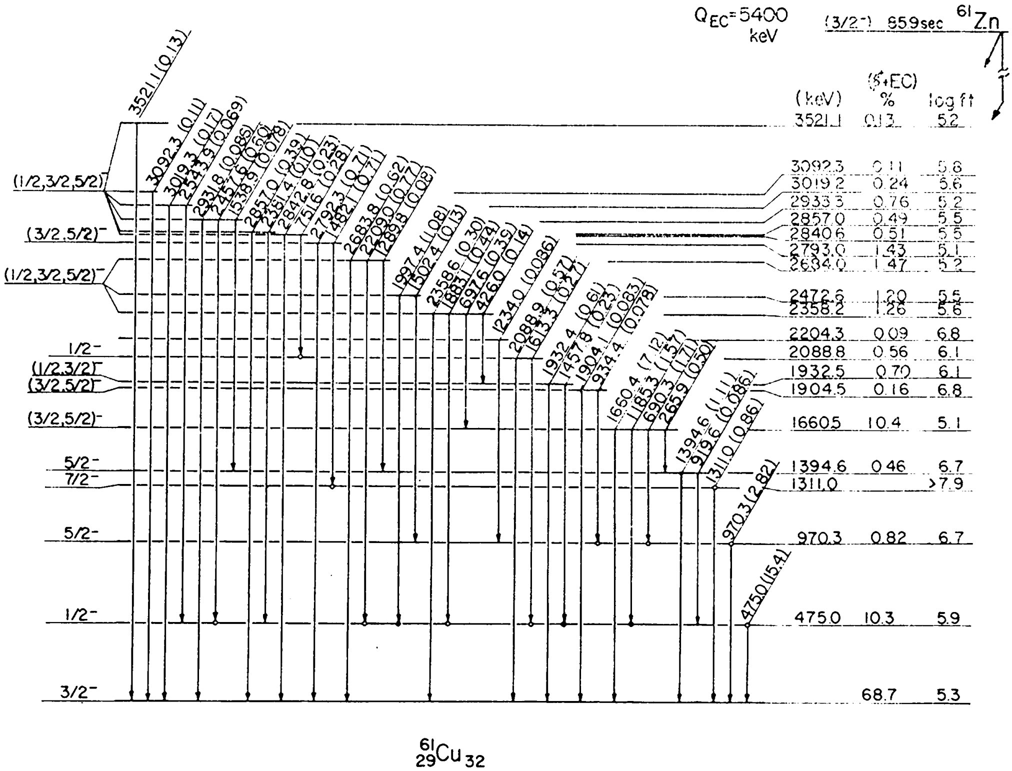

Fig. 3. Proposed scheme for the decay of 86 sec ^{61}Zn. The energies are given in keV and the transition intensities in parentheses are given per 100 decays.

Detailed arguments for the construction of the basic decay scheme of ^{61}Zn have been given elsewhere [1]), here we discuss only the additions and refinements.

The first three levels at 475.0, 970.3 and 1311.0 keV are well established [1,8]) and they were observed here to decay only to the ground state. Two weak 265.9 and 919.6 keV γ-rays are assigned to deexcite the well established [1]) levels at 1394.6 and 1660.5 keV. This assignment is supported from observed coincidences between protons and γ-rays from the $^{58}Ni(^{4}He, p)$ reaction study [8]). The level at 1904.5 keV was observed to decay and populate the ground and the 970.3 keV levels. There were no additional transitions observed that could deexcite the levels at 1932.5, 2088.8, 2472.6, 2793.0, 2840.6 and

2857.0 as reported in ref. [1]). New levels at 2204.3, and 3521.1 keV were assigned to be populated in the decay of ^{61}Zn on the basis of the observed γ-rays at 1234.0 and 3521.1 keV that deexcite these levels, respectively. These assignments were confirmed in the prompt γ-ray study [8]) of the ^{58}Ni(^{4}He, pγ)^{61}Cu reaction. A γ-ray at 267.7 keV was reported [1]) to deexcite the level at 2359.2 keV. The energy of this latter γ-ray was redetermined to be 265.9 keV and the energy of that level 2358.2 keV. Thus the 265.9 keV γ-ray was assigned to deexcite the 1660.5 keV level on the basis of (i) a better energy agreement and (ii) reaction γ-ray information [8]). Two additional γ-rays at 426.0 and 697.6 keV are assigned to deexcite the 2358.2 keV level on grounds of (i) good energy agreement and (ii) reaction γ-ray information [8]).

Two weak γ-rays at 1289.8 and 1538.9 keV were observed to follow ^{61}Zn decay and were assigned to deexcite the levels at 2684.0 and 2933.3 keV, respectively, on the basis of good energy agreement. The γ-ray at 3019.3 keV observed in the ^{61}Zn decay was confirmed [8]) to deexcite a level at 3019.3 keV in ^{61}Cu. Finally, the γ-ray at 1156.4 keV reported [1]) to possibly deexcite the level at 3092.3 keV was not observed in this study. The level at 3092.3 keV, however, was confirmed [8]) to deexcite to the ground state.

In table 2 we have summarized the levels in ^{61}Cu that have been observed to be populated in the decay of ^{61}Zn. The first two columns give the level number and the level energy. The third column gives the percent (β^+ + EC) population of each level

TABLE 2

Assignment of log ft and J^π values to levels in ^{61}Cu

Level no.	Level energy (keV)		%(β^+ + EC)		%β^+		log ft		J^π
0	0		68.7	*62*	68.1	*62*	5.3	*1*	$\frac{3}{2}^-$
1	475.0	*1*	10.3	*2*	10.1	*2*	5.9	*1*	$\frac{1}{2}^-$
2	970.3	*1*	0.82	*17*	0.80	*17*	6.7	*1*	$\frac{5}{2}^-$
3	1311.0	*1*					> 7.9		$\frac{7}{2}^-$
4	1394.6	*1*	0.46	*4*	0.44	*4*	6.7	*1*	$\frac{5}{2}^-$
5	1660.5	*1*	10.4	*2*	10.1	*2*	5.1	*1*	$(\frac{3}{2}, \frac{5}{2})^-$
6	1904.5	*2*	0.16	*4*	0.15	*4*	6.8	*1*	$(\frac{3}{2}, \frac{5}{2})^-$
7	1932.5	*2*	0.70	*4*	0.67	*4*	6.1	*1*	$(\frac{1}{2}, \frac{3}{2})^-$
8	2088.8	*2*	0.56	*4*	0.53	*4*	6.1	*1*	$\frac{1}{2}^-$
9	2204.3	*4*	0.09	*3*	0.08	*3*	6.8	*2*	
10	2358.2	*2*	1.26	*4*	1.17	*4*	5.6	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
11	2472.6	*2*	1.20	*3*	1.08	*3*	5.5	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
12	2684.0	*4*	1.47	*6*	1.27	*5*	5.2	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
13	2793.0	*2*	1.43	*3*	1.21	*3*	5.1	*1*	$(\frac{3}{2}, \frac{5}{2})^-$
14	2840.6	*3*	0.51	*4*	0.43	*3*	5.5	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
15	2857.0	*4*	0.49	*6*	0.41	*3*	5.5	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
16	2933.3	*3*	0.76	*4*	0.61	*3*	5.2	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
17	3019.2	*11*	0.24	*3*	0.18	*2*	5.6	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
18	3092.3	*13*	0.11	*2*	0.08	*2*	5.8	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$
19	3521.1	*15*	0.13	*3*	0.06	*1*	5.2	*1*	$(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$

and it is calculated from γ-ray intensities populating and depopulating each level. The value of 6.15 ± 0.30 for the ratio of positons from ^{61}Zn to the number of 475.0 keV transitions of ref. [1]) was used to calculate the value of 68.7 ± 6.2 for the percent population of the ground state in ^{61}Cu by $\beta^+ + $EC. This value thus obtained, is a function of the proposed decay scheme which is shown in fig. 3.

The percent population of each level by positon decay was calculated from the ratios EC(K)/β^+, EC(L_I)/EC(K), etc. given in pp. 575-6 of ref. [10]). The $\log ft$ values reported in the fifth column of table 2 were obtained from the present populations with the aid of the nomograms in pp. 574–3 of ref. [10]). The value of 5400 keV for Q_{EC} for the decay to the ground state was used [1]). The present values are in good agreement with the $\log ft$ values of ref. [1]).

The proposed decay scheme is shown in fig. 3 with the transition intensities given in parentheses expressed per 100 decays. With the exception of the transitions below 475.0 keV, the transitions in ^{61}Cu that follow ^{61}Zn decay have high enough energy to justify the neglection of corrections due to internal conversion. The transitions below 475.0 keV have been assumed M1 and corrections have been made using the conversion coefficients of Hager and Seltzer [11]).

The ground state of ^{61}Zn from shell-model level systematics is expected [10]) to be $\frac{3}{2}^-$ and this is substantiated from the observed $\log ft$ values to the low-lying levels in ^{61}Cu which have been shown from other evidence to be $\frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{5}{2}^-$. The ground state of ^{61}Cu must be $\frac{3}{2}^-$ on the following grounds (i) level systematics of the odd-mass Cu isotopes, (ii) the observed $l_p = 1$ value of the orbital angular momentum of the transferred proton in the ^{60}Ni(^{3}He, d)^{61}Cu reaction studies of Pullen and Rosner [3]) and (iii) the triple-correlation work on ^{60}Ni(p, $\gamma\gamma$) of Gossett and August [2]). The $\log ft$ value for the decay to the ground state is 5.3, characteristic of an allowed transition.

The 475.0 keV state is rather well established [2]) as $\frac{1}{2}^-$. The assignment $\frac{1}{2}$ was also confirmed from angular correlation studies [8]) in the ^{58}Ni(^{4}He, pγ) reaction. The negative parity assignment for this level is deduced from the $l_p = 1$ transfer in the ^{60}Ni(^{3}He, d) reaction [3]). The $\log ft$ value of 5.9 for the decay to this level is consistent with an allowed decay.

The level at 970.3 keV was populated with an $l_p = 3$ from the ^{60}Ni(^{4}He, d) reaction [3]) while the triple-correlation studies [2]) on ^{60}Ni(p, $\gamma\gamma$) have established this level as $\frac{5}{2}^-$. The $\log ft$ value of 6.7 for this level indicates some retardation for an allowed transition and a possible explanation for this was given in ref. [1]).

The two levels at 1311.0 and 1394.6 keV have been observed with an $l_p = 3$ transfer in the ^{60}Ni(^{3}He, d) reaction [3]). The 1311.0 keV level does not appear to be populated by beta decay as evidenced by the proposed scheme of fig. 3 and from the fact that several of the higher-lying levels have been observed [8]) to decay to this level by weak branches which have not been seen in the ^{61}Zn decay. A lower estimate of 7.9 for the $\log ft$ value for the decay to the 1311.0 keV level has been placed from the present evidence. This information strongly suggests that the 1311.0 keV level is $\frac{7}{2}^-$. The 1394.6 keV level is seen to be populated weakly by β-decay with a $\log ft$ value of

6.7 and it is assigned as $\frac{5}{2}^-$. This is also supported by the (p, $\gamma\gamma$) work [2]), where a state at 1370 keV was assigned as $\frac{5}{2}^-$ although the 1311 keV level was not resolved.

The 1660.5 keV level is strongly populated by β-decay with a log ft value of 5.1 suggesting a $\frac{1}{2}^-$, $\frac{3}{2}^-$ or $\frac{5}{2}^-$ assignment. This level was not seen in the ^{60}Ni(^{3}He, d) reaction while the ^{60}Ni(p, $\gamma\gamma$) work [2]) limited the probable J^π values to $\frac{3}{2}^-$ or $\frac{5}{2}^-$. This level was observed to decay to all the levels below ($\frac{1}{2}^-$, $\frac{3}{2}^-$, $\frac{5}{2}^-$) except the $\frac{7}{2}^-$ level at 1311.0 keV and this is consistent with above limits.

The level at 1904.5 keV is rather weakly populated by β-decay with a log ft value of 6.8. Since no low-lying positive parity states are expected here, in analogy with ^{63}Cu where positive parity states have been observed at 3.32 MeV and higher [12]), we may assume the β-decay to this level to be allowed, thus limiting the J^π value to $(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$. This level was seen to decay to the $\frac{3}{2}^-$ ground state and the $\frac{5}{2}^-$ state at 970.3 keV in the ^{61}Zn decay. This level was also observed [8]) to decay to the ($\frac{7}{2}^-$) 1311.0 keV level. Three closely-lying levels in the vicinity of 1930 keV were observed [8]). This makes uncertain the $l_p = 1$ assignment to a 1930 keV level from the (^{3}He, d) reaction as quoted in ref. [2]) and the assignment of $\frac{3}{2}^-$ of a level at 1890 keV. The above evidence is sufficient to limit the J^π value to the 1904.5 keV level only to $\frac{3}{2}^-$ or $\frac{5}{2}^-$.

The level at 1932.5 keV is populated by β-decay with a log ft value of 6.1 indicating that this is probably an allowed decay. This and the exclusive decay to the ($\frac{3}{2}^-$) ground and the ($\frac{1}{2}^-$) 475.0 keV states limit the most probable J^π value for this level to $\frac{1}{2}^-$ or $\frac{3}{2}^-$.

A level at 2070 was assigned as $\frac{1}{2}^-$ from the ^{60}Ni(p, $\gamma\gamma$) work [2]) and this is identified with the 2088.8 keV level from this work. This level is populated by beta decay with a log ft value of 6.1 and decays only to $\frac{1}{2}^-$ and $\frac{3}{2}^-$ levels below. This is consistent with the $\frac{1}{2}^-$ assignment.

The level at 2793.0 keV is populated by an allowed beta transition (log ft = 5.1) and it decays to the ($\frac{3}{2}^-$) ground and ($\frac{7}{2}^-$) 1311.0 keV states. This information limits the J^π value for this level to $\frac{3}{2}^-$ or $\frac{5}{2}^-$.

The levels at 2358.2, 2472.6, 2684.0, 2840.6, 2857.0, 2933.3, 3019.2, 3092.3 and 3521.1 keV are populated by allowed β-decays (log $ft \leqq 5.8$) and decay to $\frac{1}{2}^-$, $\frac{3}{2}^-$ and/or $\frac{5}{2}^-$ levels below. This information is only sufficient to limit the J^π value for these levels to $(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$.

Finally the level at 2204.3 keV is only very weakly populated in β-decay and the presently available γ-ray information does not allow one to limit the J^π value for this level.

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