sion coefficients calculated for the 260.3-, 507.2-, and 548.3-keV transitions indicate an $M1$ character for them. Of these, the first two populate levels of spin $2^+$. This information excludes the value $0^+$ as a possibility for the 548.25-keV level. Similarly, the 596.6-keV transition is $M1$ in character and populates the $2^+$ level at 40.84 keV, thus excluding the $0^+$ values as a possibility for the 637.2-keV level, limiting the assignment to $1^+$.

Some of the lower-lying levels in $^{60}$Cu and $^{62}$Cu could be discussed in terms of shell-model configurations in the $j$-$j$ coupling approximation. In the decay of both $^{60}$Zn and $^{62}$Zn we may expect primarily to populate states in transitions of a $2p_{3/2}$ proton into a neutron. The most likely configuration for the ground state of $^{60}$Cu appears to be a member of $[p{:}2p_{3/2};\, n{:}(2p_{3/2})^{-1}]_J$, with $J=2^+$ as predicted by the Brennan-Bernstein coupling rules[17] on the basis of the zero-range limit with a proton-neutron residual interaction of the form $V_{ij}=V_0(0.9+0.1\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j)\delta_{ij}$. With this interaction the $3^+$ and $1^+$ states of the above configuration lie higher than the $2^+$ state, and the $0^+$ member lies even higher. Other configurations that can give rise to excited states seen in the $\beta$ decay of $^{60}$Zn are $[p{:}(2p_{3/2});\, n{:}(2p_{3/2})_0{}^2(f_{5/2})^1]_J$ ($J=1^+, 4^+, 2^+, 3^+$ in order of increasing excitation in the above zero-range limit), $[p{:}(2p_{3/2});\, n{:}(2p_{3/2})_0{}^2(2p_{1/2})]_J$ ($J=1, 2$), and others. Since these configurations do not give rise to low-lying $0^+$ states or negative-parity states, it appears safe to exclude the value of $0^+$ as a possibility for negative-parity states at least for energies up to 570 keV.

In the case of $^{62}$Cu similar configurations seem to be applicable. The ground state could be interpreted as $p{:}(2p_{3/2}){:}n{:}(2p_{3/2})^4(1f_{5/2})^1$ in agreement with the Brennan-Bernstein rule,[17] while the first excited state could be described as $p{:}(2p_{3/2}){:}n{:}(2p_{3/2})^{-1}(1f_{5/2})_0{}^2$. For a more detailed description of these nuclides a complete shell-model calculation using the effective-interaction approach[18] may be necessary. Before such a calculation becomes feasible, further experimental information about the low-lying states in the Cu isotopes will be required.

## ACKNOWLEDGMENTS

The authors wish to thank the crew of the Washington University cyclotron for performing the irradiations. The authors are most grateful for the cooperation of Dr. T. Gallagher and the personnel of the Washington University computing facilities in processing these data. National Science Foundation Grant No. G-22296 is also gratefully acknowledged.

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[17] M. H. Brennan and A. M. Bernstein, Phys. Rev. **120**, 927 (1960).

[18] N. Auerbach, Phys. Rev. **163**, 1203 (1967).

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PHYSICAL REVIEW VOLUME 177, NUMBER 4 20 JANUARY 1969

# Decay Scheme of the 86-sec $^{61}$Zn†

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The decay of the 86-sec $^{61}$Zn has been investigated using Ge(Li) and NaI(Tl) $\gamma$-ray detectors. Coincidence relationships among the $\gamma$ rays were established in $\gamma$-$\gamma$ coincidence experiments. It was found from observed coincident $\gamma$ rays that the decay of the 86-sec $^{61}$Zn populates levels at 476.3, 970.7, 1311.1, 1661.4, 1908.1, 2090.9, 2359.2, 2474.3, 2684.7, 2793.7, 2841.5, and 2932.7 keV. Levels in $^{61}$Cu at 1394.9, 1934.8, level 2858.1, 3016.8, and 3090.4 keV are proposed on the basis of observed $\gamma$-ray intensities, energy sums, and positions established from studies of nuclear reactions. May spin assignments have been made from present log$ft$ values and previously reported correlation data from studies of nuclear reactions. The half-life of $^{61}$Zn was measured and found to be $85.9\pm0.6$ sec. The levels in $^{61}$Cu are compared with previously reported theoretical calculations based on current models for the nucleus.

## I. INTRODUCTION

THE decay of $^{61}$Zn was first investigated by Cumming,[1] who assigned levels at 0.48, 0.98, and 1.64 MeV populated mainly by positron emission in the decay of $^{61}$Zn. The levels of $^{61}$Cu have been studied, however, by a number of investigators by means of scattering experiments from a variety of nuclear reactions. The most recent and definitive such work is the study of triple correlations in the $^{60}$Ni($p$, $\gamma\gamma$) $^{61}$Cu reaction by Gossett and August,[2] the ($^3$He, $d$) reaction studies of Blair,[2,3] and the $^{58}$Ni($^4$He, $p$) work of Brown and co-workers.[4]

The investigation of the decay scheme of the 86-sec

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† Work supported in part by the U.S. Atomic Energy Commission under Contract Nos. AT(11-1)-1530 and AT(11-1)-1760.

[1] J. B. Cumming, Phys. Rev. **114**, 1600 (1959).

[2] C. R. Gossett and L. S. August, Phys. Rev. **137**, B381 (1964).

[3] A. G. Blair (private communication), referred to in Ref. 2.

[4] G. Brown, J. G. B. Haigh, F. R. Hudson, and A. E. Macgregor, Nucl. Phys. **A101**, 163 (1967).

$^{61}$Zn was undertaken in order to establish the levels, the $\gamma$-ray transitions, and their coincidence relationships. This information is essential for comparison with $\gamma$-ray data from nuclear reactions induced on Ni isotopes that we are presently investigating. The decay scheme that we are proposing is primarily based on coincidence relationships between $\gamma$ rays established in this work and on energy sum rules in conjunction with information from particle work from nuclear reactions previously reported.

## II. EXPERIMENTAL PROCEDURES

### A. Production of $^{61}$Zn Samples

The $^{61}$Zn samples were produced by the ($^4$He, $n$) reaction, using the cyclotron at Washington University. The targets were 10.5-mg/cm$^2$ natural nickel foils. The maximum $^4$He-ion energy was kept below 18 MeV to avoid the $^{58}$Ni($^4$He, $2n$) and the $^{58}$Ni($^4$He, $t$) reactions producing 2.4-min $^{60}$Zn and 88-sec $^{59}$Cu, respectively. The targets were mounted on carriers in a pneumatic tube which returned the samples to the counting area in less than 5 sec after the end of bombardment. Radiochemical purification of the samples was not employed because this increased the relative activity of the 38-min $^{63}$Zn present. Counting of the samples began about 10 sec from the end of bombardment. The only long-lived activities that could be identified as contributing to the $\gamma$-ray spectra were the 38-min $^{63}$Zn and the 3.3-h $^{61}$Cu.

### B. Detection Equipment and Methods of Counting

For $\gamma$-ray counting both Ge(Li) and NaI(Tl) detectors were used. The Ge(Li) detectors had active volumes of 20 and 30 cm$^3$, with full widths at half-maximum of 2.4 and 3.0 keV for the $\gamma$ rays from a $^{137}$Cs source, respectively. The NaI(Tl) detectors used were integrally mounted 7.6×7.6-cm crystals. In some experiments a base-line restorer was employed and this allowed accumulation of data at a rate of 6000 counts/sec without appreciable loss in resolution. For $\gamma$-$\gamma$ coincidence measurements one NaI(Tl) and one 20-cm$^3$ Ge(Li) detector were used. A base-line restorer was used with the Ge(Li) detector, which allowed the accumulation of coincidence data at a rate of about 400 counts/sec, without appreciable loss in resolution. The resolving times used were between 50 and 100 nsec.

The pulse-height analysis system is described in Ref. 5.

## III. RESULTS

In order to obtain singles $\gamma$-ray spectra with good statistics from the decay of the short-lived 86-sec $^{61}$Zn many samples were counted. Many spectra from two fixed consecutive time intervals of 1.5 and 3.0 min were added to increase statistics. Comparison of the relative intensities from the two spectra thus obtained allowed identification of the $\gamma$-ray peaks with a half-life of 70–100 sec. Typical singles spectra of the 86-sec $^{61}$Zn, obtained at an early time interval of 1.5 min, are shown in Figs. 1 and 2. The $\gamma$ rays at 668, 961, and 1412 keV were identified with the decay of 38-min $^{63}$Zn and the $\gamma$ rays at 284, 655, and part of the 1185-keV peak were identified with the decay of the 3.31-h $^{61}$Cu.

Standard sources[6] of $^{57}$Co, $^{139}$Ce, $^{203}$Hg, $^{22}$Na, $^{207}$Bi, $^{60}$Co, and $^{56}$Co were used for energy calibration, and the energies were determined by least-squares fit to the centroids of the peaks. The centroids were calculated with the aid of a digital computer by fitting Gaussian curves to the data points, after subtraction of the underlying Compton background. The relative efficiencies of the $\gamma$ rays were determined from photopeak areas. The efficiency curve used was obtained using standard sources of $^{109}$Cd, $^{57}$Co, $^{203}$Hg, $^{137}$Cs, and $^{88}$Y with relative efficiencies from Ref. 6, p. 563, and $^{133}$Ba and $^{56}$Co with relative efficiencies from Refs. 7 and 8, respectively.

The energies and intensities of the $\gamma$ rays from $^{61}$Zn are summarized in Table I. The values given were obtained from at least six different spectra. For the measurement of the half-life of $^{61}$Zn the pulses from $\gamma$ rays with energy higher than 1400 keV were multiscaled for about 2 h using 12-sec counting intervals per channel. The decay curves were analyzed for exponen-

TABLE I. Energies and relative intensities of $\gamma$ rays following 86-sec $^{61}$Zn decay from $\gamma$-ray singles data.

| Energy (keV) | Relative $\gamma$-ray intensity | Energy (keV) | Relative $\gamma$-ray intensity |
|---|---|---|---|
| 267.7 ±0.3[a] | 6.7±0.7 | 1661.3±0.9 | 100.0 |
| 476.30±0.15 | 211±15 | 1884.0±0.9 | 3.8±1.1 |
| 690.9±0.8 | 21.6±2.2 | 1933.7±0.5 | 6.2±0.9 |
| 750.7±1.1 | 4.8±1.7 | 1997.7±0.9 | 16.0±0.9 |
| 936.4±2.0[a] | 0.9±0.5 | 2089.9±1.0 | 9.1±0.6 |
| 952.3±2.0[a] | 1.0±0.5 | 2209.2±0.8 | 11.6±0.7 |
| 970.70±0.13 | 36.9±1.8 | 2358.6±1.0 | 3.5±0.4 |
| 1139.5±3.0[b] | 1.8±0.8 | 2382.1±2.0[b] | 1.1±0.2 |
| 1156.4±3.0[b] | 3.3±0.8 | 2457.2±1.3 | 10.0±1.0 |
| 1185.1±0.3 | 21.7±1.5 | 2683.4±1.0 | 8.5±0.9 |
| 1311.1±0.6 | 8.9±0.5 | 2792.6±1.4 | 10.0±1.0 |
| 1394.9±0.6 | 16.4±1.7 | 2841.5±0.3 | 3.4±0.6 |
| 1459.6±0.5 | 4.4±1.2 | 2856.5±1.1 | 4.5±0.6 |
| 1483.0±0.4 | 9.5±0.5 | 2931.6±2.0[b] | 1.4±0.4 |
| 1504.9±2.0[b] | 2.4±0.5 | 3016.8±2.7 | 2.6±0.3 |
| 1614.9±0.5 | 3.8±0.8 | 3090.5±1.5 | 2.2±0.6 |

[a] $\gamma$ ray seen only in two spectra.

[b] $\gamma$ ray seen only in three spectra.

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[5] E. J. Hoffman and D. G. Sarantites, preceding paper, Phys. Rev. **177**, 1640 (1969).

[6] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed.

[7] Y. Gurfinkel and A. Notea, Nucl. Instr. Methods **57**, 173 (1967).

[8] P. H. Barker and R. D. Connor, Nucl. Instr. Methods **57**, 147 (1967).

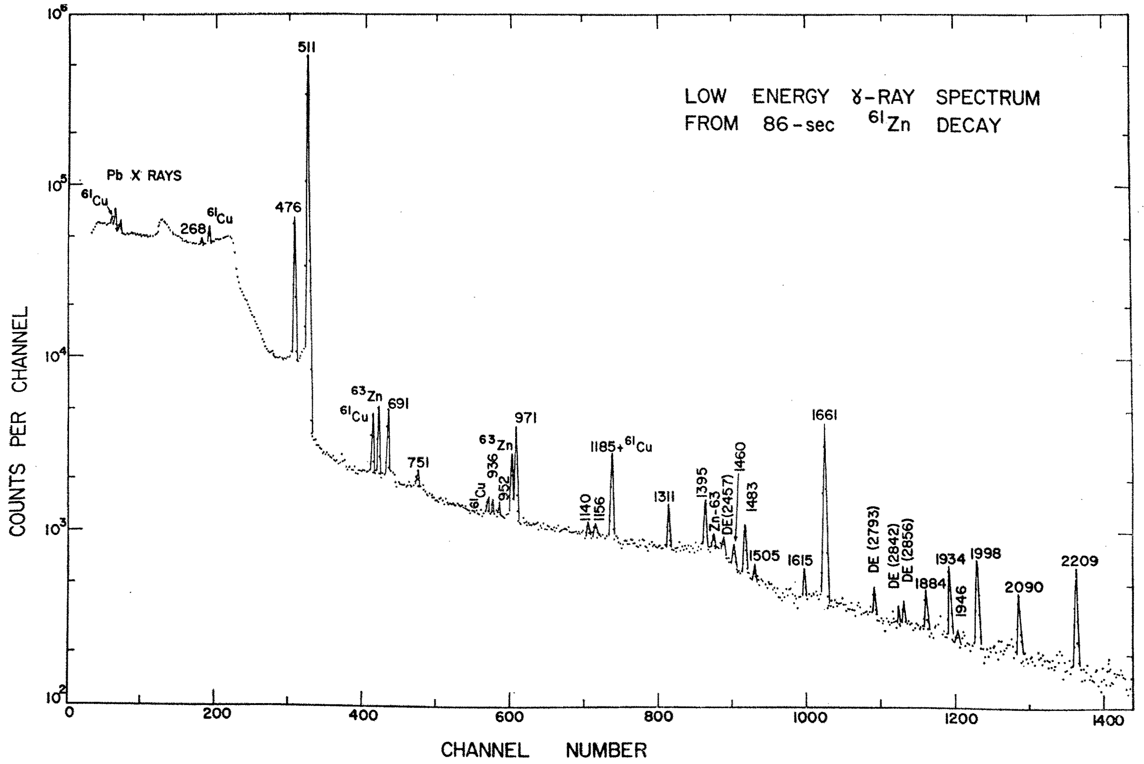

FIG. 1. Low-energy $\gamma$-ray spectrum following 86-sec $^{61}$Zn decay. The most prominent $\gamma$ rays from $^{63}$Zn and the daughter $^{61}$Cu are shown also.

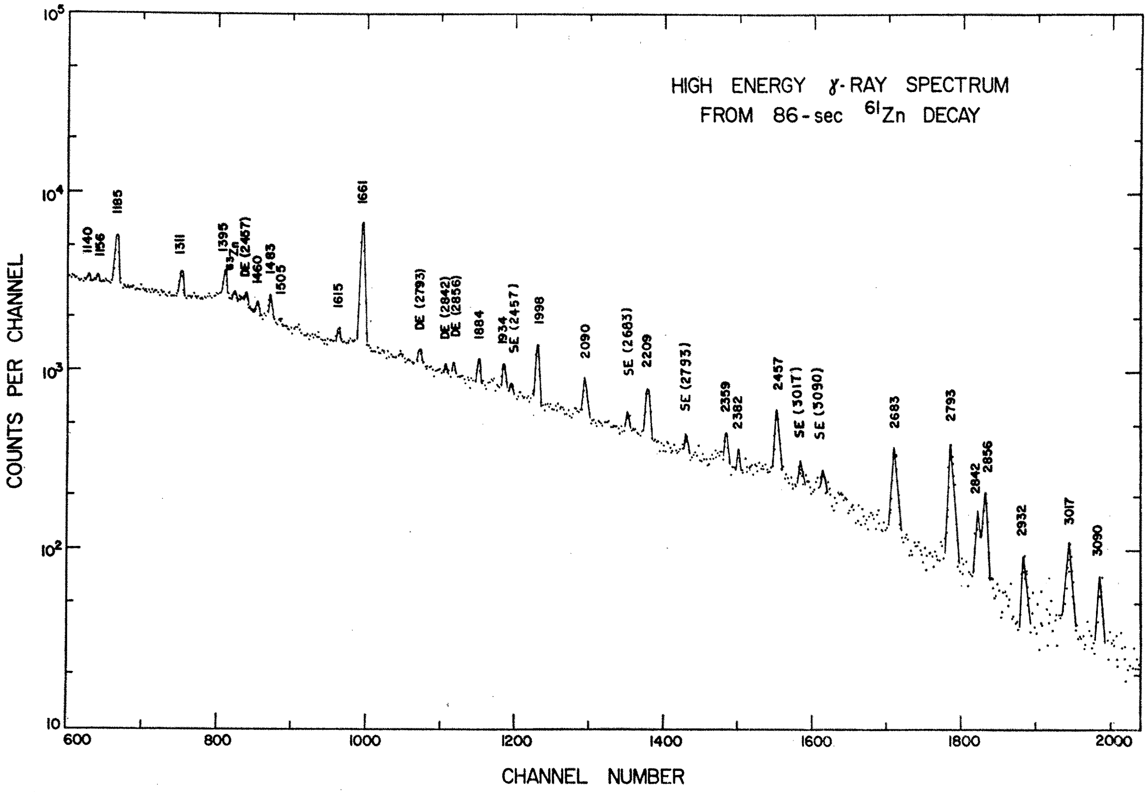

FIG. 2. High-energy $\gamma$-ray spectrum following $^{61}$Zn decay. A base-line restorer and high counting rates were employed in the accumulation of this spectrum.

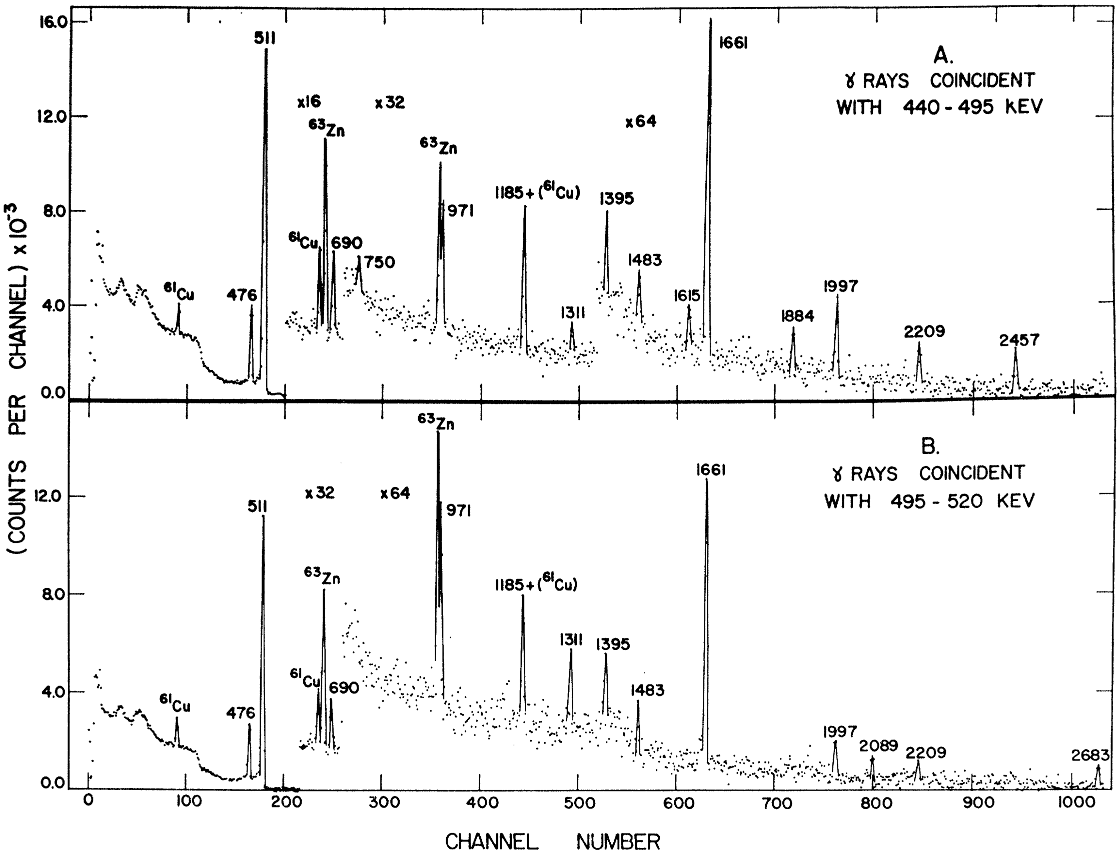

FIG. 3. (A) Shows the spectrum of the $\gamma$ rays obtained with the Ge(Li) detector coincident with the energy region 440–495 keV in NaI(Tl). (B) Shows the $\gamma$-ray spectrum obtained with the Ge(Li) detector in coincidence with the annihilation radiation (495–520 keV) in NaI(Tl) detector.

tial decay by the least-squares method and the value of the half-life of $^{61}$Zn was found to be 85.9±0.6 sec as a weighted average from three determinations.

To measure the fraction of $^{61}$Zn decays to the ground state of $^{61}$Cu spectra, displaying of the $\gamma$ rays up to 600 keV, were recorded as a function of time. The positrons were annihilated near the source and far from the detector. The value of 6.15±0.30 for the ratio of positrons from $^{61}$Zn to the number of 476-keV transitions was obtained as a weighted average from two determinations. Using the proposed decay scheme (see Sec. IV), the fraction of decay to the ground state was calculated from the above ratio to be 0.674±0.050. This result was obtained after correction for internal conversion using the theoretical estimates of Sliv and Band[9] and for electron capture using the theoretical estimates of Zweifel[10] and of Wapstra *et al.*[11] (Fig. 3 of Ref. 6, p. 575). This result is in agreement within experimental error with the value of ~0.8 of Cumming.[1]

In this study the $\gamma$-$\gamma$ coincidence spectra from the decay of $^{61}$Zn were taken with the two-parameter pulse-height analyzer operated in a 256(NaI)×1024(Ge) channel configuration, covering energy ranges of 1.9 and 2.7 MeV for the NaI(Tl) and Ge(Li) axes, respectively. In Figs. 3(A), 3(B), and 4(A)–4(C) we show the spectra taken with the Ge(Li) detector in coincidence with the indicated regions in the NaI detector.

## IV. CONSTRUCTION OF DECAY SCHEME

In Fig. 5 we show the decay scheme for the decay of the 86-sec $^{61}$Zn and below we give arguments for the proposed scheme.

The 476-, 971-, and 1661-keV $\gamma$ rays are the three most intense $\gamma$ rays and they were not seen in coincidence with each other. These $\gamma$ rays must therefore feed the ground state, thus establishing levels at 476.3, 970.7, and 1661.4 keV. The 691-keV $\gamma$ ray is in strong coincidence with the 971-keV $\gamma$ ray [Fig. 4(A)] and the sum 690.9+970.7 keV is, within experimental error, equal to 1661.4 keV. Therefore the 690.9-keV $\gamma$ ray

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[9] L. A. Sliv and I. M. Band, in *Alpha-, Beta-, and Gamma-ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Co., Amsterdam, 1965), p. 1639.

[10] P. F. Zweifel, Phys. Rev. **107**, 329 (1957).

[11] A. H. Wapstra, G. J. Nijgh, and R. VanLieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Co., Amsterdam, 1959).

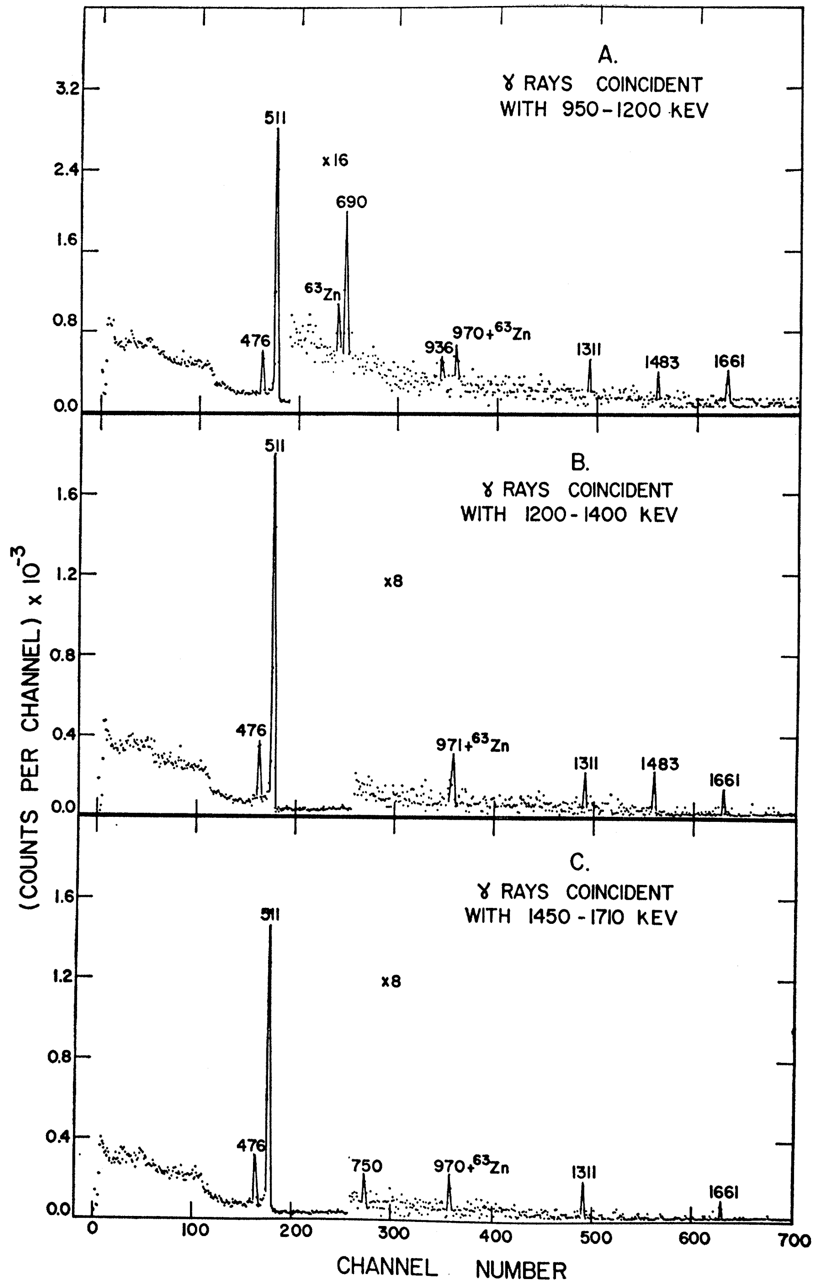

FIG. 4. γ-ray spectra obtained with the Ge(Li) detector in coincidence with the energy regions indicated in the NaI(Tl) detector.

de-excites the 1661.4-keV level and populates the 970.7-keV level. Since the 476-keV line is not resolved from the 511-keV line in the NaI spectra, to determine the γ rays coincident with the 476-keV γ ray we have integrated the energy regions 440–495 and 495–520 keV in the NaI axis and displayed the Ge(Li) spectra coincident with these two regions in Figs. 3(A) and 3(B). The 476-keV γ ray in these two spectra is due to underlying Compton shoulders of higher-energy γ rays coincident with the 476-keV γ ray and to the annihilation radiation from $\beta^+$ feeding. The coincident peaks in the 440-495-keV window that have higher intensities relative to the 476-keV peak than in the 495–520-keV window must be in true coincidence with the 476-keV γ ray. Thus we find that the 1185-, 1615-, 1884-, 1998-, 2209-, and 2457-keV γ rays are in strong coincidence with the 476-keV γ ray. The 750-keV γ ray is seen in weak coincidence with the 476-keV γ ray. The 1185-keV γ ray must feed the 476.3-keV level and de-excites the established level at 1661.4 keV.

The γ rays at 1884, 1998, 2209, and 2457 keV were not seen in coincidence with any other γ ray, and since

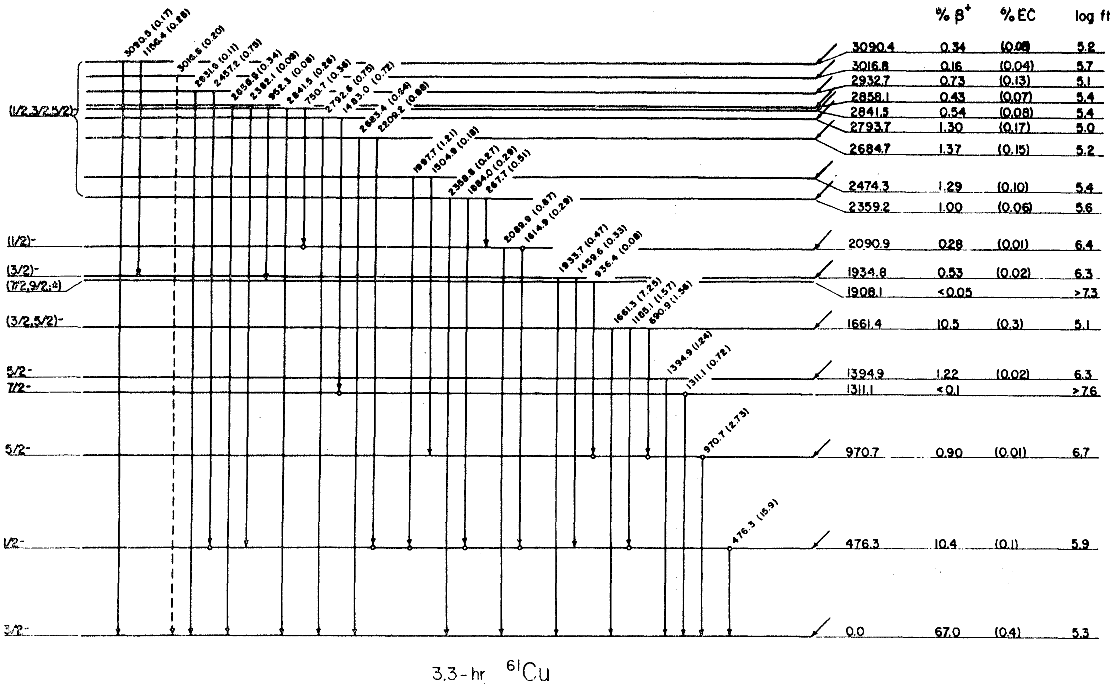

FIG. 5. Proposed decay scheme for the decay of the 85.9-sec $^{61}$Zn. All energies are given in keV and the intensities of the transitions in $^{61}$Cu are given per 100 decays of the $^{61}$Zn.

they have rather high energy, they must feed the 476.3-keV level. This establishes levels at 2359.2, 2474.3, 2684.7, and 2932.7 keV. The 2358.6-, 2683.4-, and 2931.6-keV $\gamma$ rays were assigned as crossover transitions to the ground state, on the basis of the close agreement with the energy sums. The 267.7- and 1504.9-keV $\gamma$ rays were also assigned to de-excite the 2359.2- and 2474.3-keV levels on the basis of good agreement with energy sums. The 1615-keV $\gamma$ ray is in coincidence with both the 476.3- and 750.7-keV $\gamma$ rays [Fig. 4(C)]. We have placed levels at 2090.9 and 2841.5 keV to accommodate this information and the $\gamma$ rays at 2089.9 and 2841.5 keV as crossover transitions to the ground state.

The 936-keV $\gamma$ ray was seen to be coincident with the 971-keV $\gamma$ ray [Fig. 4(A)], supporting an assignment of a level at 1908.1 keV. The 1311- and 1483-keV $\gamma$ rays appear to be in coincidence with each other, and since the former is more intense, it was assumed to feed the ground state, thus establishing levels at 1311.1 and 2793.7 keV. The 2792.6-keV $\gamma$ ray is placed as the crossover transition to the ground state.

Levels at 1934.8, 2858.1, and 3090.4 keV have been assigned on the basis of energy sums and evidence of levels populated in the $^{64}$Zn($p$, $\alpha$) reaction (see Table II).

This accommodates the 1459.6-, 1933.7-, 1946.4-, 952.3-, 2382.1-, 2856.5-, 1156.4-, and 3090.5-keV $\gamma$ rays. The $\gamma$ rays at 1394.9 and 3016.8 keV were not seen in coincidence with the 476-keV $\gamma$ ray, although they are intense enough to have been seen in the coincidence spectra. Since levels at 1394.9 and 3016.8 keV have been seen by means of the $^{64}$Zn($p$, $\alpha$) reaction (Table II), we have assigned the 1395- and 3017-keV $\gamma$ rays to de-excite these levels.

In Table II we summarize the levels in $^{61}$Cu populated in the decay of $^{61}$Zn on the basis of (a) observed coincidences, (b) energy sums of observed $\gamma$ rays in conjunction with levels excited in the $^{64}$Zn($p$, $\alpha$) reaction,[4] and (c) $\gamma$-ray energies observed in this work and levels excited in the $^{64}$Zn($p$, $\alpha$) reaction. Thus in column 1 of Table II we give the energy of the assigned levels, obtained as the weighted average from column 3. In column 2 we give the transition energies observed that have a sum equal to the level energy. In column 3 we give the sum of the transition energies of the assumed cascades originating from the corresponding level. In column 4 the standard deviation is given in keV for each energy sum. In columns 5 and 6 we summarize the levels observed by Brown and co-workers[4] in the $^{64}$Zn($p$, $\alpha$) reaction and the difference from our values, respectively. It is important to notice that there is a systematic difference between our energy values and those from Ref. 4, the latter being lower by about 8 keV on the average. The proposed level scheme accommodates all the observed $\gamma$ rays with the exception of the 1139.5-keV transition.

Using the value of 5.40 MeV for $Q_{\mathrm{EC}}$ of Cumming,[1] we have calculated the log$ft$ values given in Fig. 5,

TABLE II. Levels in $^{61}$Cu. Energy sums for assigned transitions in cascade.

| Level (keV) | Transition energies | Sum (keV) | $\sigma$ (keV) | Ref. 4 ($\pm$10 keV) | Energy difference, this work and Ref. 4 |
|---|---|---|---|---|---|
| 476.3 | 476.3 | 476.3 | 0.2 | 478 | −1.7 |
| 970.7 | 970.7 | 970.7 | 0.1 | 968 | +2.7 |
| 1311.1[a] | 1311.1 | 1311.1 | 0.6 | 1306 | +5.1 |
| 1394.9[a] | 1394.9 | 1394.9 | 0.9 | 1393 | +1.9 |
| 1661.4 | 1661.3 | 1661.3 | 0.9 | 1652 | +9.4 |
| | 476.3+1185.1[b] | 1661.4 | 0.4 | | |
| | 970.7+690.9[b] | 1661.6 | 0.8 | | |
| 1908.1 | 970.7+936.4[b] | 1908.1 | 2.0 | 1897 | +11.1 |
| 1934.8[a] | 1933.7 | 1933.7 | 0.5 | 1927 | +7.8 |
| | 476.3+1459.6 | 1935.9 | 0.5 | | |
| 2090.9 | 2089.9 | 2089.9 | 1.0 | 2081 | +9.9 |
| | 476.3+1614.9[b] | 2091.2 | 0.5 | | |
| 2359.2 | 2358.6 | 2358.6 | 1.0 | 2353 | +5.6 |
| | 267.7+2090.9 | 2358.6 | 1.1 | | |
| | 476.3+1884.0[b] | 2360.3 | 1.0 | | |
| 2474.3 | 476.3+1997.7[b] | 2474.0 | 0.9 | 2466 | +8.3 |
| | 970.7+1504.9 | 2475.6 | 2.0 | | |
| 2684.7 | 2683.4 | 2683.4 | 1.0 | 2673 | +11.7 |
| | 476.3+2209.2[b] | 2685.5 | 0.8 | | |
| 2793.7 | 2792.6 | 2792.6 | 1.4 | 2785 | +8.7 |
| | 1311.1+1483.0[b] | 2794.1 | 0.7 | | |
| 2841.5 | 2841.5 | 2841.5 | 0.3 | 2834 | +7.5 |
| | 2090.9+750.7 | 2841.6 | 1.5 | | |
| | 476.3+1614.9+750.7[b] | 2841.9 | 1.2 | | |
| 2858.1[a] | 2856.5 | 2856.5 | 1.1 | 2849 | +6.7 |
| | 476.3+2382.1 | 2858.4 | 2.0 | | |
| | 970.7+936.4+952.3 | 2859.4 | 3.0 | | |
| 2932.7 | 2931.6 | 2931.6 | 2.0 | 2917 | +15.7 |
| | 476.3+2457.2[b] | 2933.5 | 1.4 | | |
| 3016.8[a] | 3016.8 | 3016.8 | 2.7 | 3010 | +6.8 |
| 3090.4[a] | 3090.5 | 3090.5 | 1.5 | 3083 | +7.4 |
| | 1156.4+1934.8 | 3091.2 | 3.1 | | |

[a] Level assigned on the basis of energy sum and observed level from $^{64}$Zn($p$, $\alpha$), Reference 3.

[b] Cascade for which coincidences were observed.

with the aid of Moszkowski's nomogram.[12] The values obtained are in fair agreement with those given by Cumming[1] for the ground state and the 0.48-, 0.98-, and 1.64-MeV levels.

## V. ASSIGNMENT OF SPINS AND PARITIES

On the basis of the log*ft* values shown in Fig. 5 it is clear that all the states that were observed to be populated by $\beta^+$ decay should have negative parity and possible spins $(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})$.

The ground state of $^{61}$Cu must be $\frac{3}{2}^-$ based on systematics of the odd-mass Cu isotopes and consistent with the log*ft* value, the orbital angular momentum of the transferred proton ($l_p=1$) from $^{60}$Ni($^3$He, $d$)$^{61}$Cu studies of Blair,[3] and the triple-correlation work on $^{60}$Ni($p$, $\gamma\gamma$) of Gossett and August.[2] The 476-keV state was rather well established to be $\frac{1}{2}^-$ from the work of the latter authors. This state was also characterized by an $l_p=1$ transfer in the $^{60}$Ni($^3$He, $d$) reaction.[3] The state at 971 keV was populated with an $l_p=3$ transfer in the $^{60}$Ni($^3$He, $d$) reaction,[3] and the triple-correlation studies[2] on $^{60}$Ni($p$, $\gamma\gamma$) have established the value $\frac{5}{2}^-$ for this state. This assignment is in agreement with the observed retardation of $\beta^+$ decay to this level (log*ft* of 6.7), which may be due to partial one-phonon admixture to this state (see Sec. VI). The states at 1311 and 1395 keV are rather interesting. These states have been seen with $l_p=3$ transfer in the $^{60}$Ni($^3$He, $d$) reaction.[3] The 1311-keV state is not populated in the $\beta^+$ decay and a lower limit of 7.6 for the log*ft* value to this state has been estimated from our data. This 1311-keV level decays to the ground $\frac{3}{2}^-$ state. Decay to the 476-keV $\frac{1}{2}^-$ state was not observed and an upper limit for the intensity of such transitions can be placed at 0.08

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[12] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

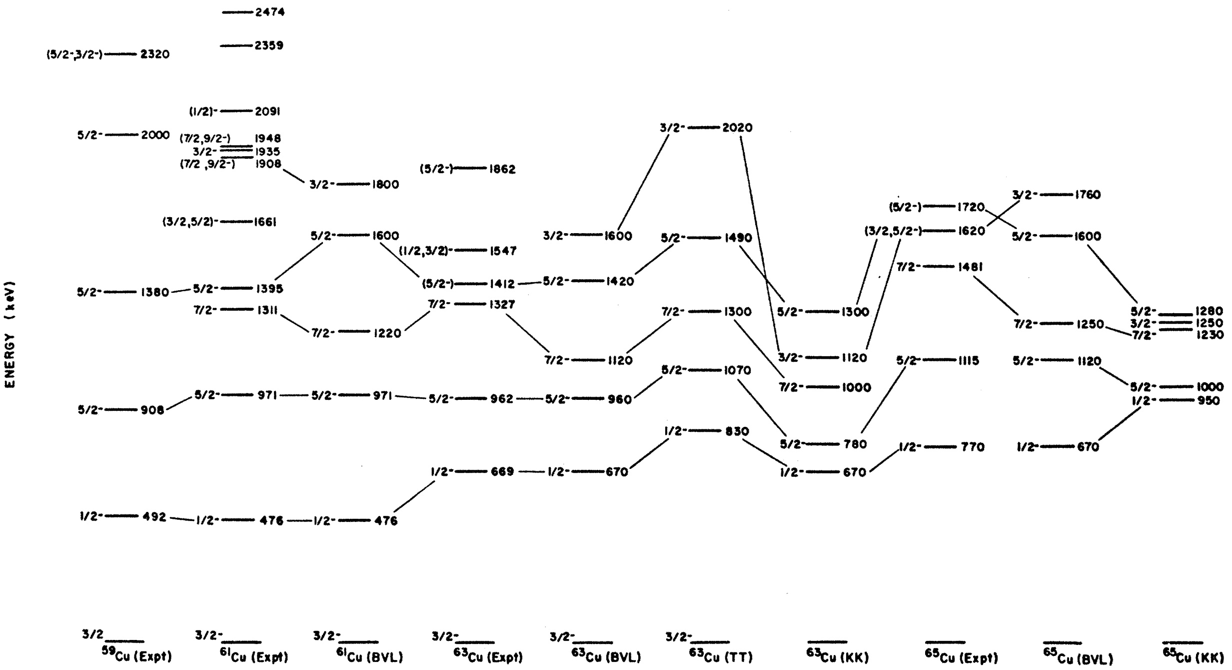

FIG. 6. Comparison of experimental energy levels of the odd-mass Cu isotopes with various theoretical predictions. The experimental data presented are from this work, from Ref. 6, and from P. A. Treado, C. R. Gosslett, and L. S. August, Nucl. Phys. **A112**, 32 (1968). Levels labeled BVL are calculated in Ref. 16, those labeled TT are from Ref. 17, and those labeled KK are from Ref. 18.

for 100 $^{61}$Zn decays. This information strongly supports a $\frac{7}{2}^-$ assignment for the 1311-keV state. The 1395-keV level is assigned as $\frac{5}{2}^-$ on the basis of the fact that it is populated in $\beta^+$ decay and from the value of 3 for $l_p$ assigned by Blair.[3] This assignment is also supported by the $(p, \gamma\gamma)$ work,[2] where a state of 1370 keV was assigned as $\frac{5}{2}^-$, while the 1311-keV state was not resolved. The 1661-keV state was not excited in the ($^3$He, $d$) reaction, while the $(p, \gamma\gamma)$ work[2] supports a $(\frac{3}{2}, \frac{5}{2})^-$ assignment. From our data it is not possible to limit the spin assignment any further without knowledge of the multipolarities of the transitions involved. The state at 1908 keV is not populated in $\beta^+$ decay, and since no low-lying positive-parity states are expected here, in analogy with $^{63}$Cu, where positive-parity states have been identified at 3.32 MeV and higher,[13] we propose an assignment of $\frac{7}{2}^-$ or $\frac{9}{2}^-$ for this state. A state at 1930 keV with $l_p=1$ from ($^3$He, $d$) is quoted in Ref. 2, and a state at 1890 keV is characterized as $\frac{3}{2}^-$ by the same authors. We believe that these values may refer[2] to our state at 1935 keV populated in $\beta^+$ decay, and we therefore have assigned this state as $\frac{3}{2}^-$. A level at 2070 from the $(p, \gamma\gamma)$ work[2] was assigned as $\frac{1}{2}$. We believe that this is the same with our level at 2091 on the basis of systematic difference of about 20 keV between the levels reported by the latter authors and this work. Finally, for the levels at 2359–3090 keV no more definite than $(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^-$ spin and parity assignment can be made on the basis of the presently available data.

## VI. INTERPRETATION OF LEVELS

Our work is in good agreement with the previously reported simple decay scheme of Cumming.[1] Our data are also consistent with the reaction work of Blair[3] and of Gossett and August.[2] Using the combined information of log*ft* values together with the reaction data, we were able to make more definite spin assignments for most of the lower-lying states in $^{61}$Cu. The interest in the level scheme of $^{61}$Cu lies in the fact that the spectra of the odd-mass Cu isotopes have been extensively analyzed recently in terms of essentially the single-particle vibrating-core model.[14–17] The calculations of Bouten and VanLeuven[16] consider core excitations up to two phonons and the proton is allowed to move in the $2p_{3/2}$, $1f_{5/2}$, or $2p_{1/2}$ orbital about the core. These calculations included Cu isotopes from 59 to 65.

A more recent calculation of Thankappan and True[17] has considered the particle core interaction to include

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[13] B. G. Harvey, J. R. Meriwether, A. Bussiere, and D. J. Horen, Nucl. Phys. **70**, 305 (1965).

[14] B. F. Bayman and L. Silverberg, Nucl. Phys. **16**, 625 (1960).

[15] M. Harvey, Nucl. Phys. **48**, 578 (1963).

[16] M. Bouten and P. VanLeuven, Nucl. Phys. **32**, 499 (1962).

[17] V. K. Thankappan and W. True, Phys. Rev. **137**, B793 (1964).

a dipole-dipole and a quadrupole term, including an off-diagonal coupling of the phonon and the single particle. This calculation was limited to $^{63}$Cu and included only one-phonon excitation.

In a more recent article, Kisslinger and Kumar[18] have reported preliminary results of calculations based on the assumption that the collective and quasiparticle motion are independent and have further allowed for anharmonicity in the vibrational motion of the core.

In Fig. 6 we present a comparison of the experimental data on the levels of the odd-mass Cu isotopes with some of the pertinent calculations. The columns abbreviated BVL are the calculations of Bouten and VanLeuven,[16] those abbreviated TT are the results of Thankappan and True,[17] and those abbreviated KK are the results of Kisslinger and Kumar.[18] Note that although the results of BVL appear to be in good agreement with experiment for the $^{61-65}$Cu isotopes, these calculations were based on selecting the single-particle spacings to fit the energies of the first two excited states for an assumed strength of the core-particle interaction. It is interesting to note that in the BVL calculation the $p_{1/2}$-$p_{3/2}$ and $p_{1/2}$-$f_{5/2}$ spacings had to be reduced somehow for $^{61}$Cu relative to $^{63}$Cu in order to fit the data and that the proton-core interaction strength was raised for $^{61}$Cu relative to $^{63}$Cu. In all the $^{61-65}$Cu isotopes the predictions for the $\frac{7}{2}^-$ state were lower than experiment, while the predictions for the second $\frac{5}{2}^-$ state were high.

The results of TT for $^{63}$Cu gave, in general, satisfactory agreement with experiment and it is worth noticing that the $\frac{3}{2}^-$ from the coupling of the $p_{3/2}$ proton with the one-phonon core state lies quite high in excitation.

Finally, a comparison of the $^{63}$Cu and $^{65}$Cu results of KK is included. Note that the agreement of these calculations with experiment does not appear to be as satisfactory, although these calculations are more realistic. This is perhaps due to the fact that these authors have not attempted to obtain the best possible fit to these data.

In summary, it can be concluded that the interpretation of the levels of the odd Cu isotopes is based upon coupling of the odd proton with the first and second phonon states of the vibrating core. The coupling of the particle-phonon is not weak and therefore these states are complex in nature. From the lowest-lying states it appears that the ground state is primarily of single-quasiparticle character. The first excited state has significant $p_{1/2}$ admixture.[17] The first $\frac{7}{2}^-$ state has rather pure configuration obtained by coupling the $p_{3/2}$ quasiparticle with the $2^+$ one-phonon state of the core. The first two $\frac{5}{2}^-$ states are expected to have strong admixture to the pure $f_{5/2}$ quasiparticle from the coupling of the $p_{3/2}$, $p_{1/2}$, and $f_{5/2}$ and the one-phonon state of the core.

The first $\frac{3}{2}^-$ state, arising from the coupling of the $\frac{3}{2}^-$ proton with the one-phonon state of the core, is expected to lie high in excitation. It is interesting to notice that the log$ft$ values measured for the $\beta^+$ decay to the states $\frac{1}{2}^-$, $\frac{5}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$ at 476, 971, 1395, and 1935 keV, respectively, are higher by about one unit, compared to the decay to the ground state. As was mentioned earlier, these four states are expected to contain significant admixtures of the proton $\frac{3}{2}^-$ quasiparticle coupled with the one-phonon state of the core. The ground state of $^{61}$Zn, a $p_{3/2}$ neutron state, is expected to be primarily pure single quasiparticle in character. We may therefore expect that decay to states containing phonon-coupled components will be retarded relative to decay to pure quasiparticle states. The state at 1661 keV is strongly populated in $\beta^+$ decay of $^{61}$Cu, but this state was not excited by the $^{60}$Ni($^3$He, $d$) reaction[3] and this suggests that this state does not have appreciable single-proton character. It is conceivable that this state can be described in terms of a neutron excited to the $p_{1/2}$ subshell. More of such neutron states should be expected to be found at higher excitation energies.

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[18] L. S. Kisslinger and K. Kumar, Phys. Rev. Letters **19**, 1239 (1965).