Decay of Cu^{61} and Energy Levels in Ni^{61}†

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(Received 22 December 1966)

The 3.3-h positron decay of Cu^{61} has been investigated by use of Ge(Li) detectors and coincidence techniques. A total of 19 γ-ray transitions have been observed ranging in energy from 67 to 2120 keV, of which only eight had been reported previously. The decay scheme based on these data incorporates all of these transitions and requires only those Ni^{61} levels that have been excited in nuclear reactions. The excitation energies of the levels observed to be populated in Ni^{61} from the decay of Cu^{61} are 67.3, 282.8, 655.7, 908.8, 1100.2, 1132.4, 1185.5, 1446.9, 1611.8, 1730.2, and 2119.8 keV.

I. INTRODUCTION

THE low-lying excited states of $_{28}Ni_{33}{}^{61}$ have been investigated repeatedly in studies[1–4] of the γ radiation following the 3.3-h positron decay of $_{29}Cu_{32}{}^{61}$, as well as in various nuclear-reaction studies.[5–8] The Ni^{61} nucleus contains five neutrons in excess of the doubly closed $f_{7/2}$ shell of the $_{28}Ni_{28}{}^{56}$ core. These neutrons presumably occupy the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ single-particle orbitals.[9,10] This nucleus, therefore, is especially suitable for detailed shell-model calculations. Unfortunately, there are serious discrepancies among the previously reported experimental studies of the decay of Cu^{61}. The present investigation was undertaken in an attempt to clarify and unify the experimental situation and to allow for a meaningful comparison with theoretical calculations.

The present work employed high-resolution Ge(Li) detectors in both singles and coincidence γ-ray spectroscopic investigations. In the course of this investigation, a number of levels were found to be populated which had not been reported previously in studies of this decay. A total of 19 γ-ray transitions (only eight of which had been reported previously) were observed in the present study and have been incorporated into a level scheme that requires only those states reported in investigations of nuclear reactions.

II. SOURCE PREPARATION AND EXPERIMENTAL PROCEDURE

The $Co^{59}(\alpha,2n)Cu^{61}$ reaction was used to produce the 3.3-h Cu^{61} activity. A metallic cobalt foil target was bombarded with 29-MeV α particles from the Argonne 60-in. cyclotron. For most of these studies the Cu activity was separated from the target material by solvent extraction. After bombardment, the target material was dissolved in HNO_3 and some Cu carrier was added. The solution was dried, and the residue was taken up in 1.2*N* HCl and transferred to a separatory funnel. After mixing the solution with Cupferon and chloroform, the organic layer containing the Cu activity was separated from the aqueous layer and washed several times with 1.2*N* HCl. Finally, the Cu activity was back-extracted by adding a small amount of NaOH. A suitable fraction of the activity thus obtained was placed in plastic capsules 10 mm in diam and 20 mm high.

All spectra were recorded at least 4 h after bombardment in order to allow the 24-min Cu^{60} activity to decay through several half-lives. As a check on possible contaminants, the spectrum of a piece of unprocessed Co foil was observed 4 days after bombardment. The lines seen in this spectrum could be identified[11] with the decay of Co^{57}, Co^{58}, and Ni^{57}. The 37-h Ni^{57} activity was attributed to the $Ni^{58}(\alpha,\alpha n)Ni^{57}$ reaction on Ni impurities present in the target. At the same time, the spectrum of the chemically processed fraction showed only a very weak Co^{58} line at 810.5 keV; all lines attributable to the decay of Cu^{61} were absent.

Although the half-lives of all transitions observed in the Cu^{61} spectrum were followed carefully and found to be consistent with 3.3-h, some of the lines were too weak to permit an accurate lifetime determination. For this reason, additional runs were made with a source prepared in the Argonne isotope separator. All transitions that were observed in the chemically separated Cu^{61} source were seen again. Since there is no known isotope of mass 61 with a half-life long enough to interfere, this was taken as strong evidence that the $Cu^{61} \rightarrow Ni^{61}$ identification was correct.

The γ-ray spectra were taken in a defined geometric arrangement by use of a 3-cc Ge(Li) detector. The

† Work performed under the auspices of the U. S. Atomic Energy Commission.
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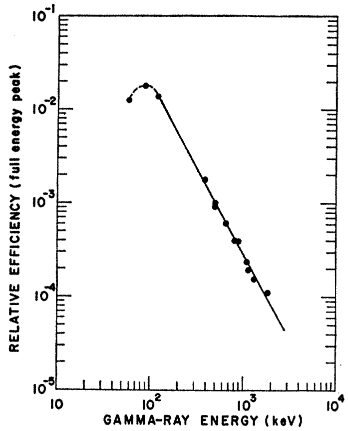

FIG. 1. Relative efficiency of the 3-cm³ Ge(Li) diode for detection of the full-energy peak. The curve, plotted as a function of γ-ray energy, is based on sources calibrated with a 3 in.×3 in. NaI(Tl) detector.

resolution width was typically 4 keV at 1.2 MeV. Corrections for any nonlinearities present in the electronic system were made with the aid of a precision pulser and digital voltmeter.[12] The values of the energy standards employed were those compiled by Marion.[13]

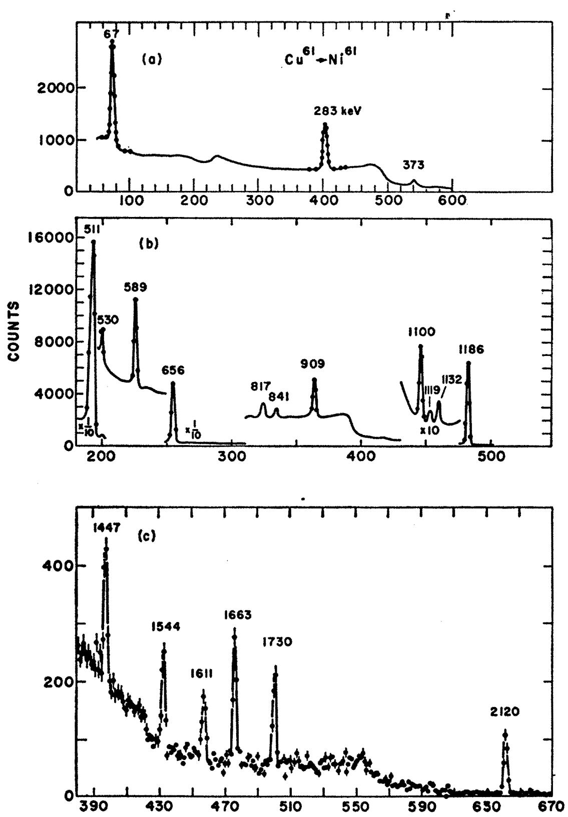

FIG. 2. γ-ray spectrum following the decay of Cu^{61}, as observed with the 3-cm³ Ge(Li) detector. The energies are in keV. The high-energy portion of the spectrum (c) was recorded with a 0.25-in. Pb absorber between the source and detector.

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The detector efficiency at the full-energy peak was determined as a function of γ-ray energy (Fig. 1) by use of sources whose disintegration rates had been carefully determined with an NaI(Tl) detector.[14] The detector was kept at a constant distance of ~0.6 cm from the source. The large uncertainty in the measurements of the intensities of the weaker lines resulted primarily from difficulties in accurately determining the peak areas. This resulted in variations of the order of 40% for the weakest lines.

A typical singles γ-ray pulse-height spectrum is shown in Fig. 2. In obtaining the high-energy portion of the spectrum, displayed in Fig. 2(c), line broadening due to pileup effects was avoided by introducing a 0.25-in. Pb absorber to reduce the intensity of the low-energy portion of the spectrum. Nevertheless, a counting time of 10 h was required to obtain this portion of the spectrum. The observed transitions and measured intensities are summarized in Table I.

III. DECAY SCHEME

The proposed decay scheme, shown in Fig. 3, is based primarily upon the energy balance of the various γ rays. The energy sums of the cascades agree within the quoted error limits with the energies of the crossover transitions. The ground-state transitions shown in this decay scheme correspond to levels observed in nuclear reactions.[5–8] The energy levels from various experimental studies are summarized in Table II. The more intense low-energy transitions were observed in coincidence with annihilation radiation by use of two Ge(Li) detectors mounted 90° apart. The coincidence

TABLE I. Transition energies and intensities of γ rays observed in the Cu^{61} decay. The uncertainty in the γ-ray energy is ±0.5 keV in each case.

γ-ray energy (keV)	γ-ray intensities (per 100 annihilation quanta)	(% per decay)
67.3	3.92 ±0.39	5.00 ±0.50
282.8	11.67 ±0.58	14.89 ±0.75
372.7	1.60 ±0.16	2.04 ±0.20
529.6	0.16 ±0.08	0.20 ±0.10
588.4	0.84 ±0.25	1.07 ±0.32
655.7	7.90 ±0.40	10.08 ±0.50
817.5	0.20 ±0.10	0.25 ±0.13
841.2	0.13 ±0.06	0.17 ±0.08
908.8	0.76 ±0.08	0.97 ±0.10
1100.2	0.18 ±0.06	0.23 ±0.08
1117.8	0.034±0.010	0.043±0.013
1132.4	0.047±0.014	0.060±0.018
1185.5	2.61 ±0.13	3.33 ±0.17
1446.9	0.034±0.010	0.043±0.013
1544.6	0.023±0.007	0.029±0.009
1611.8	0.021±0.006	0.027±0.008
1663.2	0.035±0.010	0.045±0.013
1730.2	0.033±0.010	0.042±0.013
2119.8	0.030±0.010	0.038±0.013

[14] These sources were kindly provided by D. W. Engelkemeir, Chemistry Division, Argonne National Laboratory.

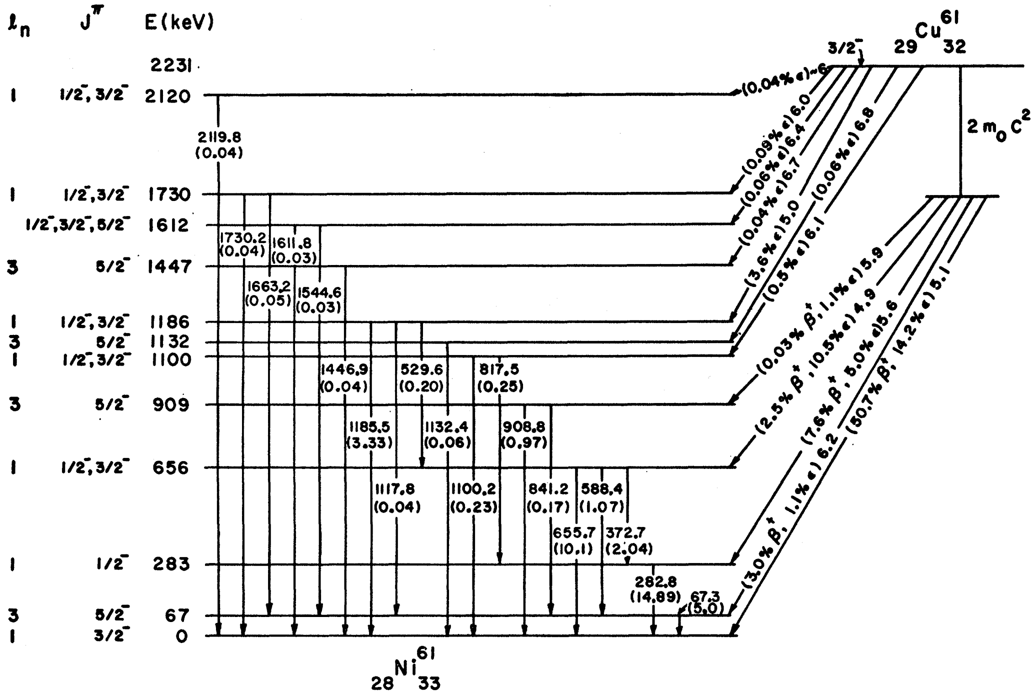

FIG. 3. Proposed decay scheme of Cu^{61}. All energies are in keV. The γ-ray intensities in percent per decay are given in parentheses. The positron- and electron-capture populations of the levels in Ni^{61} were calculated from the γ-ray intensity balance in the proposed decay scheme and the theoretical allowed positron-to-electron-capture ratios. All spins and parities are those derived from previously reported studies of charged-particle reactions and are consistent with, but not assigned on the basis of, this proposed decay scheme.

spectrum so obtained is displayed in Fig. 4. The intensities of the observed lines are in excellent agreement with those expected on the basis of the proposed decay scheme. Unfortunately, the lines at 841 and 909 keV were too weak to be observed in the coincidence spectrum.

Since a 940-keV γ ray, observed with an NaI spectrometer,[3] had previously been attributed to a transition between the 1186- and 283-keV levels,[15] a coincidence spectrum was taken with the analyzer gated on the 283-keV γ ray. The result is shown in Fig. 5. However, no evidence was found for a 909–283-keV cascade. The height of the expected 909-keV coincidence peak, based on the observed intensities of the singles

TABLE II. Level energies (keV) in Ni^{61}.

	From Cu^{61} decay			Nuclear reactions							
	$Cu^{61}(\beta^+)Ni^{61}$		$Ni^{61}(\alpha,\alpha'\gamma)$	$Ni^{60}(d,p)Ni^{61}$			$Ni^{60}(n,\gamma)Ni^{61}$	$Ni^{61}(p,p'\gamma)$			
This work ±0.5	Ref. 3	Ref. 4	Ref. 5	Ref. 6	Ref. 7	Ref. 8	Ref. 17	Chupp *et al.*[a]	l	J	π
67.3	70±1	70±2	70±1	68	68	69	···	67.40±0.01	3	$\frac{5}{2}$	—
282.8	280±3	282±3	283±3	284	284	290	280±15	···	1	$\frac{1}{2}$	—
655.7	660±10	659±3	657±7	···	660	654	···	···	1	$\frac{1}{2}, \frac{3}{2}$	—
908.8	···	···	890±10	···	915	908	···	···	3	$\frac{5}{2}$	—
···	···	···	···	···	1019	1019	···	···			
1100.2	···	···	···	1104	1104	1105	1100±30	···	1	$\frac{1}{2}, \frac{3}{2}$	—
1132.4	···	···	···	···	1137	1139	···	···	3	$\frac{5}{2}$	—
1185.5	1220±50	1192±5	···	1190	1190	1195	···	···	1	$\frac{1}{2}, \frac{3}{2}$	—
1446.9	···	···	···	···	1460	1454	···	···	3	$\frac{5}{2}$	—
1611.8	···	···	···	···	1616	1622	···	···		$\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$	—
1730.2	···	···	···	1735	1735	1750	1740±30	···	1	$\frac{1}{2}, \frac{3}{2}$	—
					1812						
					1994						
					2007						
					2023						
2119.8	···	···	···	2127	2127	2133	2150±30	···	1	$\frac{1}{2}, \frac{3}{2}$	—

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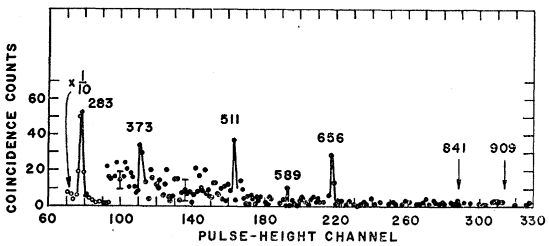

FIG. 4. Spectrum in coincidence with annihilation radiation, obtained with two Ge(Li) detectors at 90° and corrected for accidental coincidences. All energies are in keV.

spectra, is indicated in Fig. 5. It should be noted that no correction for chance coincidences was applied to this coincidence spectrum. The measured true-to-chance ratio was ~10/1. The presence of the 283-keV peak in this spectrum is due mainly to real coincidences with that portion of the Compton distribution of the 373-keV γ ray which underlies the 283-keV transition in the coincidence-gate region. As confirmatory evidence, Fig. 5 also shows a coincidence spectrum taken at the same time with a window of identical width but gated on the Compton distribution just above the 283-keV peak.

Since the coincidence spectrum of Fig. 5 shows no evidence of a 909–283-keV cascade, and since the disagreement between the energy sum $(282.8\pm0.5)+(908.8+0.5)=1191.6\pm1.0$ keV and the observed energy of the 1185 ± 0.5 γ-ray transition amounts to several times the probable error, the existence of the cascade is rejected. Instead, the 908.8-keV γ ray has been attributed to a transition from the 908-keV level in Ni^{61} observed in studies of the $Ni^{60}(d,p)Ni^{61}$ reaction.[6–8] Fagg, Geer, and Wolicki[5] also observed a line at 890 ± 10 keV in Coulomb-excitation experiments on Ni^{61}, but at that time they were unable to establish the position of this transition. The existence of the 909-keV level is further supported by the (908.5 ± 1.0)-keV sum of the 841.2–67.3-keV cascade shown in the decay scheme (Fig. 3).

The double-escape peaks of the 2119.8- and 1611.8-keV γ rays nearly coincide with the observed lines at 1100.2 and 588.4 keV. However, the ratio of the intensity of the double-escape peak to that of the full-energy peak was ~1 at $E_\gamma=2$ MeV and ~0.3 at $E_\gamma=1.6$ MeV. These ratios for the detector employed were based on the ratios observed for the 1927-keV γ ray in Ni^{57}, the 1836-keV γ in Y^{88}, and the 1675-keV γ in Co^{58}, together with a comparison with calculations of Wainio.[16] Thus, the intensity expected from the contribution of the double-escape peak of the 2119.8-keV transition is only $\sim\frac{1}{3}$ of the intensity of the 1117.8-keV line [Fig. 2(b)] and is obviously too small to account for the 1100.2-keV line which is 20 times as strong. A correction for the contribution from the double-escape peak of the 2119.8-keV γ ray amounts to only 5% of the intensity of the 1100.2-keV peak. Similarly, the contribution of the double-escape peak from the 1611.8-keV transition accounts for less than 0.2% of the observed intensity of the 588.4-keV γ ray.

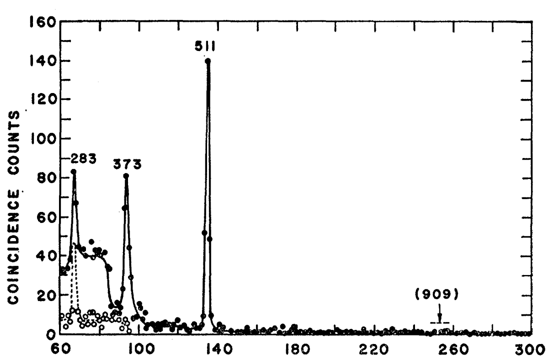

FIG. 5. Spectrum in coincidence with the 283-keV γ ray, obtained with two Ge(Li) detectors. The dashed curve indicates the coincidence contribution from the Compton distribution of the 373-keV transition. No correction for accidental coincidences has been made.

The positron- and electron-capture populations of the levels in Ni^{61} were calculated from the γ-ray intensity balance in the proposed decay scheme and the theoretical allowed positron–to–electron-capture ratios. The total internal-conversion coefficient $\alpha=0.11$ measured by Nussbaum *et al.*[3] was used in the case of the 67.3-keV ground-state transition. The resulting intensities agree with those of the lines observed by Nussbaum *et al.* to within their quoted uncertainties.

The levels observed to be populated above an excitation energy of 1186 keV have been found to be excited in (d,p) reactions[6–8]; but they had not been seen in earlier studies of the Cu^{61} decay. In addition, the 1730- and 2120-keV levels have also been established in the slow-neutron-capture γ-ray studies of Adyasevich *et al.*[17]

The spin and parity assignments are based primarily on the angular-momentum transfer observed in the deuteron-stripping experiments and the $\log ft$ values of the β-decay branches from Cu^{61}. The spin of the 283-keV level receives further confirmation from angular-correlation studies.[18,19] The results of the low-lying Ni^{61} levels, both from the present work and previous investigations, are summarized in Table II.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to M. Oselka and the cyclotron group for the many bombardments, and to J. Lerner and the isotope separator group who performed the mass separation. Thanks are also due to D. W. Engelkemeir for the use of the calibrated sources.

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