Multiparticle configurations in the odd-neutron nuclei ^{61}Ni and ^{67}Zn populated by decay of ^{61}Cu, ^{67}Cu, and ^{67}Ga†

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The decay of ^{61}Cu to levels of ^{61}Ni and the decay of ^{67}Cu and ^{67}Ga to levels of ^{67}Zn have been studied in detail. The half-life of ^{67}Ga is measured to be 3.261 ± 0.001 days. Also, absolute intensities are reported for the γ rays from the decay of ^{67}Ga. Transition probabilities are calculated for ^{61}Ni using a shell model and a modified surface δ interaction.

[RADIOACTIVITY Chemically separated sources; measured E_γ, I_γ, deduced ^{61}Ni and ^{67}Zn levels J, π; Compton suppression.]

INTRODUCTION

Recently we have shown that for many odd-mass vibrational nuclei in the medium-mass region ($60 < A < 140$) the inclusion of three-particle clustering[1–6] or a dressed, multiquasiparticle formalism[7–10] helps considerably to explain the observed level density. Also, there is evidence that the intrusion of a high-spin non-normal parity orbit in a shell (e.g., the $h_{11/2}$ orbit in the g-d-s shell) greatly affects the vibrational character of a nucleus. Apparently, in even-even tellurium ($Z = 52$) and molybdenum ($Z = 42$) nuclei the $h_{11/2}$ neutron orbit is an influence in softening the core as the neutron number increases beyond shell closure.[11–13]

The presence of the $g_{9/2}$ orbital in the p-f shell may also contribute extra levels.[1,14,15] In odd-mass arsenic ($Z = 33$) isotopes, isolated positive parity states are found between 500 and 1000 keV. In germanium ($Z = 32$) and zinc ($Z = 30$) nuclei the intrusion of the $g_{9/2}$ neutron orbit in the p-f shell probably also contributes to decreasing the quadrupole vibration energy with increasing neutron numbers even before $N = 40$.

Thus, to separate multiparticle states from intruder states lighter nuclei must be explored. Nickel nuclei offer a closed-proton shell and are low enough in neutron number that the high-spin $g_{9/2}$ orbital remains at a high excitation energy and thus does not strongly interact with the low-lying excited states. For such reasons, we chose ^{61}Ni and ^{67}Zn as nuclei which ought to provide a useful test case for shell model cluster calculations.

Recently shell-model energy level calculations have been published for the Ni and Cu isotopes by Koops and Glaudemans[16] (KG). We have extended these in order to calculate the transition probabilities for ^{61}Ni. These calculations use a model space which consists of the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits without restrictions. Of the two residual interactions we consider, the modified surface δ interaction's (MSDI) four parameters were fitted to a hundred levels in Ni and Cu ($A = 57$–66) to obtain effective two-body matrix elements. A second interaction we used was an adjusted surface δ interaction (ASDI), where, to improve the calculated energy spectra, the MSDI matrix elements were adjusted independently in an interactive least-squares fitting procedure.

Decay data for ^{61}Cu have recently been compiled by Auble.[17] The last published studies of ^{61}Cu decay cited were by Bérand *et al.*[18] in 1967 and Ritter and Larson[19] in 1969. Since that time a number of spectroscopic reaction studies have identified other levels and have led to questions concerning the decay schemes that have been proposed.

The data available on the decay of ^{67}Cu and ^{67}Ga are given in a recent NDS compilation.[20] However, a number of discrepancies associated with the γ-ray intensity data remain.[21] Also, our preliminary value of the half-life of ^{67}Ga is the value adopted by NDS.[22] We report here our final value of this half-life as well as detailed measurements of the

^{67}Cu and ^{67}Ga decays, with particular attention to the branching ratios for the γ rays originating from the 887.69-keV level. We note, for example, that only an estimate of the intensity of the 703-keV transition is given in the NDS compilation and that the 91-keV γ-ray intensity is not a measured value but is calculated from the ^{67}Cu decay scheme.

EXPERIMENTAL PROCEDURE

^{61}Cu source preparation and measurement

The ^{61}Cu was produced by bombarding a cobalt foil target with α particles from the 223.5-cm cyclotron at the Lawrence Berkeley Laboratory (LBL). The target was chemically processed (see next section for Cu separation) to yield ^{61}Cu, which was then examined with a variety of Ge(Li) detectors, including a Compton-suppression spectrometer.

^{67}Cu source preparation

The ^{67}Cu was produced by the ^{67}Zn(p,n)^{67}Cu reaction and isolated by standard radiochemical separation procedures.[23] The ^{67}Cu source material was further purified by precipitation of CuS, extraction into isooctyl thioglycolate from 0.1 M HCl, and finally precipitation as CuSCN.

^{67}Ga source preparation

The ^{67}Ga was produced at the LBL 223.5-cm cyclotron by the ^{65}Cu(α, 2n)^{67}Ga reaction. To assure the high purity required for our measurements, we developed a special chemical procedure. After dissolving the copper target, we extracted the ^{67}Ga out of 6 M HCl into diethyl ether. Following washing of the ether fraction with additional 6 M HCl, the gallium was back-extracted into H_2O. The gallium was then precipitated as $Ga(OH)_3$, dissolved in 6 M HCl and scavenged with $Fe(OH)_3$, which was precipitated with 10 M NaOH. These purification steps were then repeated, after which the solution was adjusted to a pH between 3.3 and 3.6 with formic acid. The gallium was extracted into 0.4 M thenoyl-trifluoroacetone (TTA) in benzene. The TTA-benzene was washed with 1 M NaOH and with 1 M HCl, after which the gallium was back-extracted into 12 M HCl. The gallium was finally precipitated with NH_4OH and ignited at 950° to yield Ga_2O_3.

Measurement of ^{67}Cu and ^{67}Ga sources

Both ^{67}Cu and ^{67}Ga sources were counted using LEPS and large-volume Ge(Li) spectrometers. The ^{67}Ga was also measured in two other ways: In one, we measured the spectra using a high purity Ge Compton-suppression spectrometer. In the other series, measurements were made with up to 12.5 mm of Pb absorber between the ^{67}Ga source and the large-volume Ge(Li) detector. The γ-ray energies of each source were determined by counting the ^{67}Cu and ^{67}Ga sources simultaneously with standards having precisely known energies.[21] All spectra were analyzed on the LLL CDC-7600 computer via the code GAMANAL.[24]

Separately prepared sources of ^{67}Ga were counted on the LLL Nuclear Chemistry Division automatic counting facility.[21,24-26] Several sources were alternately counted with a long-lived standard over a period of 20 half-lives. During this period the samples were assayed with a Ge(Li) spectrometer to ensure that ^{67}Ga was the only activity still present. More complete details of such half-life measurements are given in Refs. 2, 25, and and 26.

Samples for the absolute intensity measurements were prepared at the New England Nuclear[26] 91.4-cm cyclotron by the ^{65}Cu(α, 2n)^{67}Ga reaction. Activity for counting was taken from assay samples of actual pharmaceutical production lots of processed ^{67}Ga citrate. The activity was allowed to decay for at least 24 h before counting to ensure the depletion of ^{66}Ga impurity introduced during the cyclotron bombardment of the zinc target. Some of the solution was counted with a Ge(Li) detector to ensure the absence of the 511-keV annihilation peak, which is common to both ^{66}Ga and ^{68}Ga impurities. After we verified the absence of the annihilation peak, we prepared samples for ion-chamber assay by directly pipetting a portion of the sample. Solutions of ^{67}Ga citrate were counted with a high-resolution (2 keV full width at half maximum) Ge(Li) spectrometer and a 4π digital-electrometer ionization chamber.

RESULTS

In Table I we present the γ-ray energies and intensities for the ^{67}Cu decay. Our most accurately

TABLE I. Energies and intensities of γ rays from decay of ^{67}Cu.

E_γ (ΔE_γ) (keV)	I_γ (ΔI_γ) (γ rays per 100 decays)[a]
91.266(5)	7.0(1)
93.311(5)	16.1(2)
184.577(10)	48.7(3)
208.951(10)	0.115(5)
300.219(10)	0.797(11)
393.529(10)	0.220(8)

[a] Based on 20% β^- feeding of the ground state (Ref. 20) and by using 12% $E2$ (Ref. 20) for the 184-keV transition.

TABLE II. Absolute intensities for the more abundant γ rays in the decay of ^{67}Ga.

E_γ	Relative intensity NEN[a]	LLL[b]	γ abundance (%) (Δ%)[c]
91.3 93.3	2.53[d]	2.41[d]	40.5(8)
184.6	1.263	1.233	20.2(4)
208.9	0.144	0.140	2.3(1)
300.2	1.000	1.000	16.0(5)
393.5	0.287	0.280	4.6(2)

[a] New England Nuclear.
[b] Lawrence Livermore Laboratory.
[c] The quoted error is an estimate of the error in *relative* intensity, based on Ge(Li) counting; the overall probable error, including the comparison to ion-chamber data, is estimated to be ±5%.
[d] Sum of 91.3- and 93.3-keV γ-ray intensities.

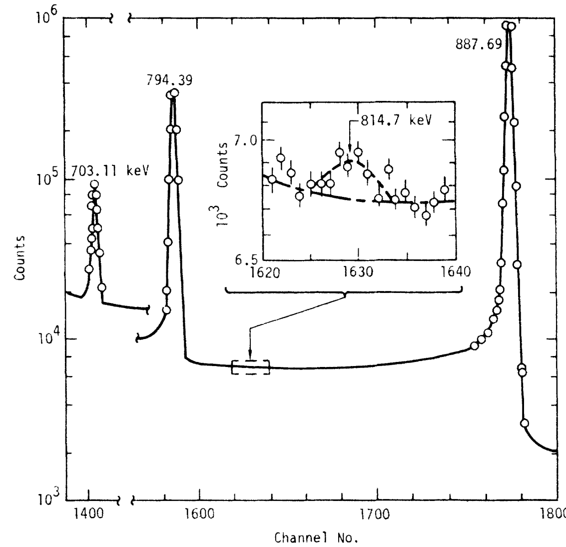

FIG. 1. (a) γ rays of ^{67}Ga from 700 to 900 keV observed using a large-volume Ge(Li) detector in conjunction with 12.5 mm of lead between the source and the detector; (b) shows detail of region near 814.7 keV.

measured value for the half-life of ^{67}Ga is 3.261 ±0.001 days.[22] The absolute ^{67}Ga γ-ray intensities are given in Table II, and the full set of intensity values for ^{67}Ga is given in Table III. In Fig. 1 we show the high-energy region of the ^{67}Ga spectrum taken with a 12.5-mm lead absorber between source and detector. The insert shows an enlargement of the area of the spectrum where we identify the possible presence of an 814.7-keV γ ray. The ratio of the intensities of the 91- and 93-keV γ rays is significantly different than that adopted by Auble[20] from previous works. In Fig. 2 we show the separation of the 91- and 93-keV γ

TABLE III. Energies and intensities of γ rays from decay of ^{67}Ga.

E_γ (ΔE_γ) (keV)	I_γ (ΔI_γ) Relative[a]	Per 10^3 decays[b]	Assignment From	To
91.266(5)	80.0(3)	29.6(6)	184	93
93.311(5)	1000(3)	370(7)	93	g.s.
184.577(10)	552(2)	204(4)	184	g.s.
208.951(10)	62.8(3)	23.3(6)	393	124
300.219(10)	448(1)	166(3)	393	93
393.529(10)	125.4(5)	46.4(1)	393	g.s.
494.169(15)	1.83(2)	0.68(2)	887	393
604.44[c]	d	d	604	g.s.
703.110(15)	0.292(9)	0.108(8)	887	184
794.386(15)	1.37(5)	0.509(15)	887	93
814.7(5)	e	0.0002(1)	814	g.s.
887.693(15)	3.88(2)	1.44(2)	887	g.s.
979(1)	f	f	979	g.s.

[a] Fitting error only (add 1% in quadrature for error in the overall efficiency curve).
[b] The absolute efficiency of the Ge(Li) spectrometer is incorporated in these values.
[c] Value adopted from Ref. 20.
[d] We do not observe this γ ray and place a limit on its intensity of less than 4×10^{-8} per decay of ^{67}Ga.
[e] We observe this γ ray with an intensity of 2×10^{-7} per ^{67}Ga decay in the spectra taken with the highest resolution and a 12.5-mm lead absorber between source and detector.
[f] We cannot positively identify any of the γ rays that might be associated with the 979-keV level and place a limit of 1×10^{-8} per decay on their intensity.

rays in the LEPS spectrum. In Fig. 3 we present the areas of our spectra where γ rays associated with the decay of the 604.4- and 979-keV levels might be.

The γ rays that were observed to follow the 205-min half-life of ^{61}Cu are given in Table IV.

DECAY SCHEMES

Decay scheme for ^{67}Cu and ^{67}Ga

In Fig. 4 we present the decay scheme of ^{67}Cu and ^{67}Ga. We include in the figure all the known levels of ^{67}Zn below 1.0 MeV in order to discuss

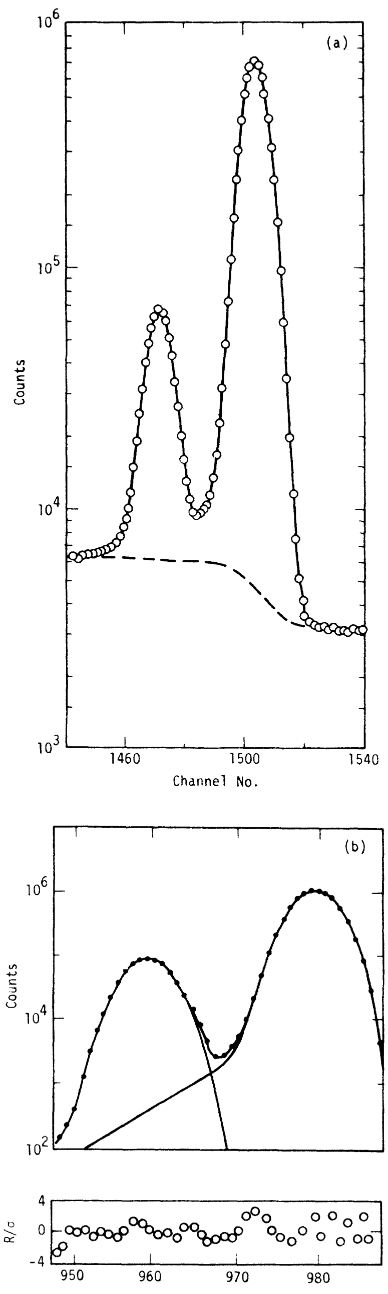

FIG. 2. (a) Spectrum of ^{67}Ga showing the separation of the 91- and 93-keV γ rays, (b) lines fitted by GAMANAL computer code of the peaks in (a).

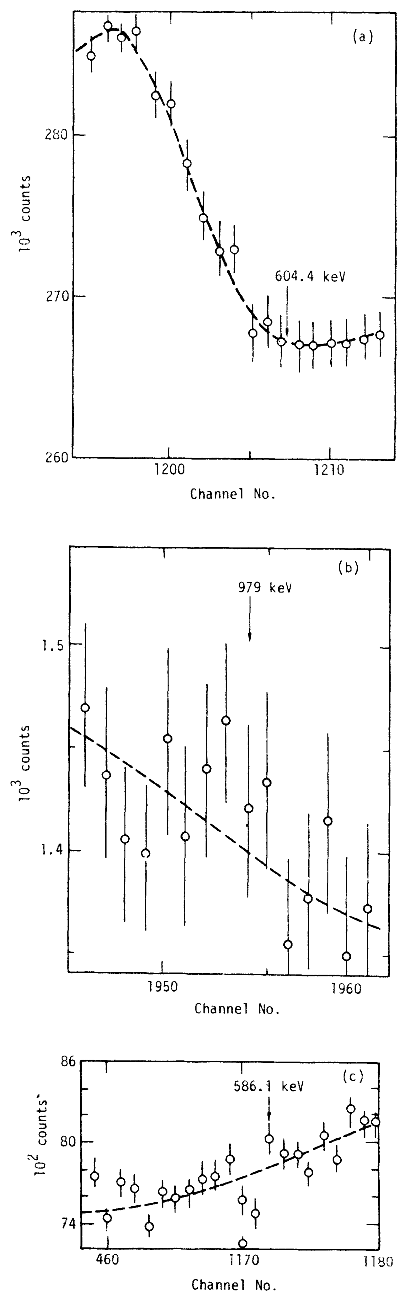

FIG. 3. Areas of ^{67}Ga spectrum showing where intensity limits were set for energies of γ rays known from other types of experiments: (a) 604.4-keV γ ray, (b) 979-keV γ ray, and (c) 586.1-keV γ ray.

the limits of population by β decay or γ-ray cascade. The J^{π} values shown are those adopted by Auble.[20] The logft values for the ^{67}Cu decay are only approximate because the ground-state feeding has not been measured precisely. Both the ^{67}Cu and ^{67}Ga logft values were calculated from the tables of Gove and Martin.[29] Our precise value for the half-life of ^{67}Ga and our measurement of the absolute intensities from ^{67}Ga decay allow us to reduce the error in the ^{67}Ga logft values to 0.01 units. Our value of 6.31 for the ground-state logft value compares well with our ^{61}Cu data. In ^{61}Cu we measure the $p_{3/2} \to f_{5/2}$ Δl-hindered-allowed β decay to have a log ft value of 6.4. Few other cases of this β transition strength have been determined experimentally.

TABLE IV. γ-ray energies and intensities observed in the decay of ^{61}Cu.

E_γ (ΔE_γ) (keV)	I_γ (ΔI_γ) (Relative)	Assignment From	To
67.412(3)	315(10)	67	g.s.
190.79(12)	0.40(8)	1099	908
215.55(18)	0.36(9)	282	67
276.688(53)	2.1(2)	1185	908
282.956(2)	1000(a)	282	g.s.
373.050(5)	172(5)	656	282
443.5(1)	0.3(1)	1099	656
529.169(22)	33(6)	1185	656
588.605(9)	96(1)	656	67
625.605(24)	4.0(3)	908	282
629.90(25)	0.5(2)	729	1099
656.008(4)	853(20)	656	g.s.
701.1(3)	0.9(2)	1609	908
816.692(13)	28.9(6)	1099	282
820.89(17)	1.8(2)	1729	908
841.211(17)	19.8(8)	908	67
902.294(20)	7.2(2)	1185	282
908.631(17)	97(3)	908	g.s.
(947.4(4))	0.2(1)	1014	67
(1014.8(4))	< 0.1	1014	g.s.
1032.162(27)	5.3(9)	1099	67
1064.896(20)	4.8(4)	1132	67
1073.465(25)	4.3(3)	1729	656
1089.11(–)	≤0.05	1997	908
1099.560(19)	22.7(8)	1099	g.s.
1117.822(43)	3.9(3)	1185	67
1132.351(32)	7.9(3)	1132	g.s.
1185.234(15)	295(6)	1185	g.s.
1446.492(19)	4.0(2)	1729	282
1542.204(23)	2.7(1)	1609	67
1609.625(48)	2.2(2)	1609	g.s.
1662.000(19)	4.2(2)	1729	67
1729.473(18)	6.4(4)	1729	g.s.
1840.7(2)	0.14(4)	2123	282
1997.73(85)	0.3(1)	1997	g.s.
2123.432(35)	3.2(1)	2123	g.s.

[a] Fiducial.

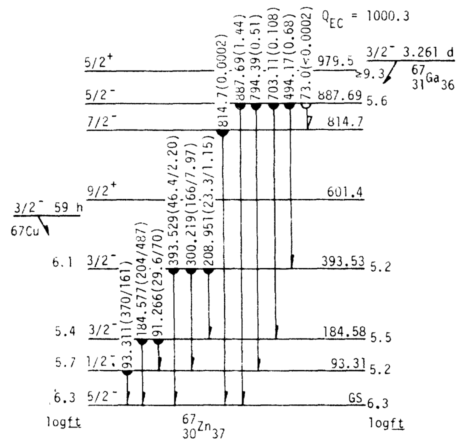

FIG. 4. Decay scheme for ^{67}Cu and ^{67}Ga. The γ-ray intensities are given per 10^3 decays as (^{67}Ga/^{67}Cu). All known levels of ^{67}Zn below 1 MeV are shown for purposes of comparison.

Auble has adopted $\frac{7}{2}^-$ as the J^{π} value for the 814.7-keV level of ^{67}Zn.[20] In our higher-energy spectra with lead absorbers, we observed the 814.7-keV γ ray with an intensity of 2×10^{-7} per ^{67}Ga decay (see Fig. 1 insert). This intensity, if ascribed solely to population by β decay, would represent a logft of at least 11.2 for this $\frac{3}{2}^-$ to $\frac{7}{2}^-$ transition. Based on the log ft systematics of Raman and Gove,[27] second-forbidden nonunique β transitions (such as that to the 814.7-keV level) normally have logft values >12. Thus, most of the feeding of the 814.7-keV level is probably due to an undetected 73-keV $M1$ transition from the 887.69-keV level.

We do not observe population of the known positive-parity levels in ^{67}Ga. Although population of the 604.4-keV $\frac{9}{2}^+$ isomer is not expected, decay to the 979-keV $\frac{5}{2}^+$ level is possible. Our limit on the population of this latter level is 10^{-8} per ^{67}Ga decay and represents a log$ft \geq 9.3$. This high value is consistent with the expected hindrance of a transition from a $\frac{3}{2}^-$ single-particle ground state to a $\frac{5}{2}^+$ level with a predominantly $g_{9/2}$ multiparticle character.

Decay scheme for ^{61}Cu

The decay scheme for ^{61}Cu to levels in ^{61}Ni is shown in Fig. 5. The branching to the ground state has been taken from NDS,[28] and theoretical E.C./β^+ ratios[29] have been used along with γ-ray intensity balances in calculating the β branching and logft values. Recently Wadsworth *et al.*[30–32] have studied the levels of ^{61}Ni by reaction spectroscopy. Their ^{58}Fe $(\alpha, n)^{61}$Ni reaction study included angular distributions and linear polarizations which set J^{π}

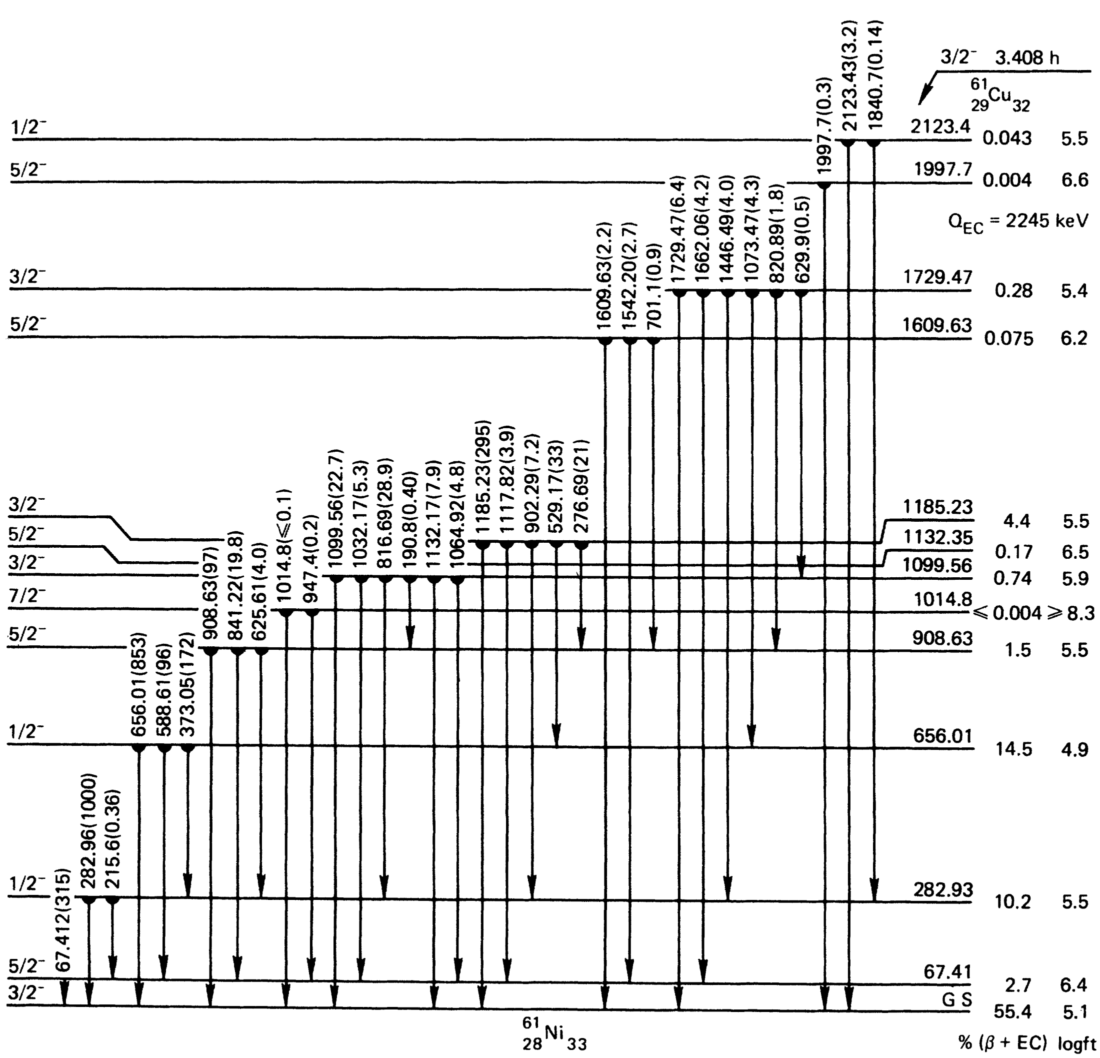

FIG. 5. Decay scheme for ^{61}Cu.

values for the following levels (J^π in parentheses): 1015($\frac{7}{2}^-$), 1454($\frac{7}{2}^-$), 1609($\frac{5}{2}^-$), 1807($\frac{9}{2}^-$), 1987($\frac{7}{2}^-$), 1997($\frac{5}{2}^-$), 2018($\frac{7}{2}^-$), 2121($\frac{9}{2}^+$), and 2129($\frac{11}{2}^-$) keV. In addition they state a strong preference of $J^\pi = \frac{1}{2}^-$ for the 656-keV level.

We find no evidence for the previously proposed level at 1019 keV.[20] We do, however, observe population of the 1014-keV level known from Coulomb excitation[20] and ^{58}Fe$(\alpha, n\gamma)^{61}$Ni reaction studies.[30-32] As the 1014-keV level has J^π of $\frac{7}{2}^-$ it is more likely fed by a γ-ray cascade than by direct electron-capture decay of ^{61}Cu. One possibility is that this level is fed from the 1997-keV level. If we use the branching ratios of Wadsworth *et al.*[30] for decay of the 1997-keV level in combination with our intensity of the 1997-keV γ ray we obtain a 1014-keV level feeding of 0.05 units. The remaining intensity could well originate from other levels.

In ^{62}Ni(d, t) and ^{62}Ni(^{3}He$, \alpha)$ studies, the level at 1729 keV has been assigned possible spin-parity values of $\frac{1}{2}^-$ or $\frac{3}{2}^-$. The $\frac{3}{2}^-$ assignment is preferred because the pattern of depopulation shows a fairly even distribution of intensity among the transitions to the four lowest lying states of spin $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{1}{2}^-$, and $\frac{3}{2}^-$.

DISCUSSION

A. Shell-model calculations for $^{61}_{28}$Ni$_{33}$

Shell-model calculations for the $Z = 28$ Ni nuclei were performed by Auerbach[33] as well as by Cohen, Lawson, MacFarlane, Pandya, and Soga,[34] with valence neutrons in the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits, to predict energies, spectroscopic factors, and certain electromagnetic transition

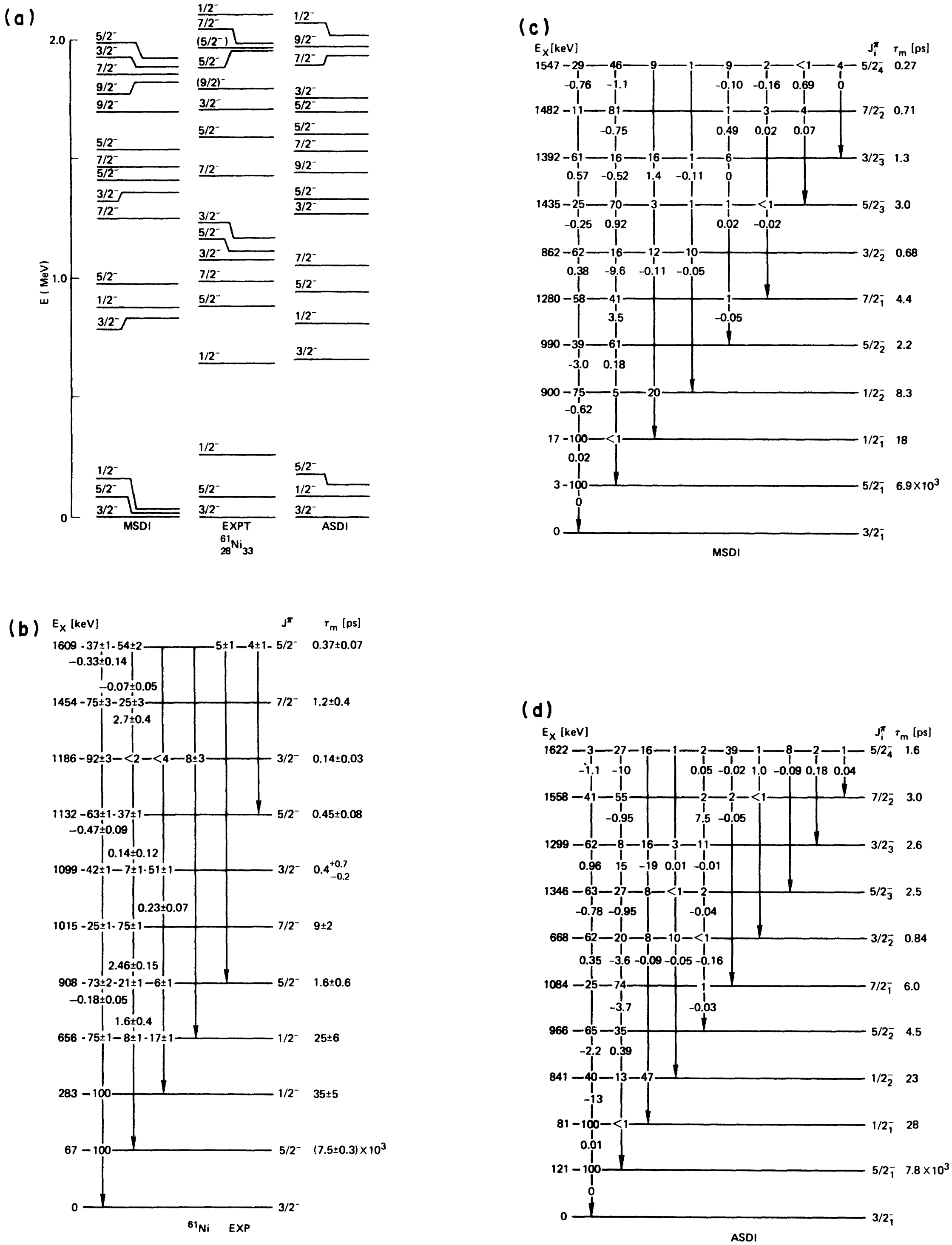

FIG. 6. The experimental and calculated γ-ray decay schemes for ^{61}Ni. The experimental data are from Refs. 30, 31, 32, and the present work. The numbers in between the energy levels (drawn in a distorted scale) are the mixing ratios, for which the sign convention of Krane and Steffen (Ref. 43) has been adopted. The calculated mean lifetimes, τ_m, have not been corrected for internal conversion. As usual, the experimental γ-ray energies have been used in the calculation of the branching, mixing ratios and lifetimes. The $E2$ strengths have been calculated with harmonic oscillator radial wave functions, with $b^2=1.03\times A^{1/3}$. Figure 6(a) shows a comparison of the energy levels, 6(b) the experimental transition probability values, 6(c) the MSDI values, and 6(d) the ASDI values.

strengths. Energy spectra have been calculated by Lawson, MacFarlane, and Kuo[35] and by Rustgi, Kung, Raj, Nisley, and Hull,[36] using a shell model with two-body matrix elements calculated from free-nucleon potentials. In addition, the goodness of the seniority quantum numbers for the Ni isotopes has been addressed by Auerbach,[33, 37] Cohen *et al.*,[34] and Hsu.[38] Glaudemans, de Voigt, and Steffens[39] have also performed detailed shell-model calculations of energy spectra and electromagnetic properties, using effective one- and two-body matrix elements.

Recently Koops and Glaudemans (KG)[16] have performed shell-model calculations for Ni and Cu isotopes with A of 57 to 68. Their model space assumed a closed ^{56}Ni core with valence-particle configurations of $(2p_{3/2})^{N_1}\,(1f_{5/2})^{N_2}(2p_{1/2})^{N_3}$, where $N_1+N_2+N_3=A-56$. No further restrictions were imposed on the configuration space; however, the dimensions of the matrices involved did not exceed 273. Further, it was assumed that the effective one- and two-body matrix elements could absorb the effect of core excitation. Rustigi *et al.*[36] have shown that no significantly better results are obtained by including excitation of two particles into the $1g_{9/2}$ orbit. As a consequence, excitation into the $1g_{9/2}$ orbit was not considered by KG.

In order to calculate the level structure of the Ni nuclei KG used two related interactions. The first was a modified surface δ interaction (MSDI)[40, 41] which is given by

$$V_{\text{MSDI}}\,(i\,,j)=-4\pi A'_T\delta(\vec{r}_i-\vec{r}_j)\delta(r_i-R)+B_T\ ,$$

where only the $T=1$ two-body matrix elements, determined by the strength parameters A'_1 and B'_1, were required. The parameter values were determined from fits of the $A=57$ to 61 and $A=62$ to 66 mass region and are discussed in detail in KG. A second calculation was made using an adjusted surface δ interaction (ASDI). Because the model space used was sufficiently large to represent the prominent properties of the low lying states in the Ni and Cu nuclei, KG made a search for the most adequate one- and two-body matrix elements. All 66 two-body matrix elements were adjusted independently in an iterative least squares fitting procedure that fit both binding and excitation energies in both Ni and Cu nuclei. Details of these calculations, their parameters, and results for binding energies, level energy spectra, and spectroscopic factors are discussed by KG. However, no calculations of electromagnetic transition probabilities in the Ni or Cu nuclei were made.

Here we use the MSDI and ASDI shell-model calculations of KG to calculate the transition probabilities for ^{61}Ni. Effective charges were fitted to a number of experimental $E2$ transition rates and a few quadrupole moments in Ni and Cu. The effective charge of the neutron following from this fit was $1.67e$ (MSDI) and $1.40e$ (ASDI). Also the effective $M1$ single-particle matrix elements were fitted to reproduce a number of experimental $M1$ transition rates and dipole moments in Ni and Cu. Explicitly, the $p_{3/2}\rightarrow f_{5/2}$ $M1$ single-particle matrix element was determined to be $0.58\mu_N$ (MSDI and ASDI) for the neutron. The same value was determined earlier by Glaudemans *et al.*[4] in a fit to $M1$ transitions in the Ni isotopes only. Both models reproduce the experimental levels up to 2.2 MeV, as well as several high-spin states above 2.2 MeV (Refs. 30 and 31). The experimental and calculated γ decay properties are shown in Fig. 6. The main decay modes can fairly well be explained within the present models. Some branching ratios poorly predicted by the MSDI model are well reproduced by the ASDI model, e.g., the decay of the $\frac{5}{2}^-_2$ and the $\frac{7}{2}^-_1$ states. In other cases, the MSDI model gives the better prediction, e.g., the decay of the second $\frac{1}{2}^-$ state. The lifetime estimates are fairly realistic except for the levels at 1132 keV and 1186 keV, where the calculated values are much too high. We conclude that the low-

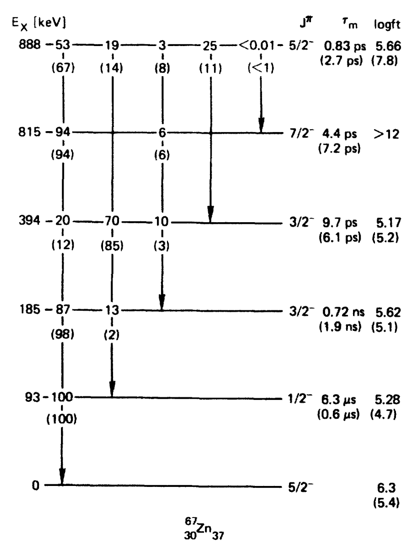

FIG. 7. The experimental energies, branching ratios, and log*ft* values for the levels of ^{67}Zn as observed in the decay of ^{67}Ga. The branching ratios and mean lifetimes in parentheses are the theoretical results of Vanden Berghe (Ref. 47). The log*ft* values in parentheses have been calculated by Van Hienen *et al.* (Ref. 47). The experimental lifetimes are taken from NDS (Ref. 20) and recent studies (Refs. 52 and 53). The branching ratio of the 815-keV level is from Neal *et al.* (Ref. 54).

er lying levels can indeed be considered as shell-model states of the rather small $(2p_{3/2},\ 1f_{5/2},\ 2p_{1/2})$ configuration space. Particular discrepancies can be attributed to the interaction or the effective operators. All cases where the sign of the calculated mixing ratio differs from the experimental one can be explained by either a very small $E2$ or a very small $M1$ transition strength. The calculated sign is then very sensitive to tiny changes in the wave function and the effective operator. Such precision is beyond the scope of the present models.

B. Cluster model and ${}^{67}_{30}Zn_{37}$ levels

Several calculations of the level structure of ${}^{67}_{30}Zn_{37}$ have been performed.[44-48] Throop, Cheng, and McDaniels[44] used a phonon-core coupling model in an attempt to account for their Coulomb-excitation data. Their calculated energy spectrum and level properties were in poor agreement with experiment. The shell-model calculation of van Hienen, Chang, and Wildenthal[47] for the Zn isotopes ($A = 60-68$) can accurately predict some of the properties of the low-lying states in these nuclei, especially energy spectra and spectroscopic factors for single neutron transfer. However, magnetic dipole transitions and β-decay strengths are not well reproduced by this model, probably because of the deficiency in the effective $M1$ operator that was used. Transitions like the $\frac{3}{2}^-_1 \to \frac{5}{2}^-_1$ have predominantly $M1$ character and are considerably affected by the $p_{3/2} \to f_{5/2}$ single-particle matrix element, which effectively should not be taken to be zero.

In a recent calculation, Vanden Berghe[48,49] has described ${}^{67}Zn$ as a cluster of three neutron holes coupled to quadrupole vibrations of the core (Alaga model).[47-50] This model gives a good account of the energies of the low-lying levels of ${}^{67}Zn$, and also gives reasonable γ decay predictions if the $p_{3/2} \to f_{5/2}$ $M1$ single-particle transition (l forbidden only in zeroth order) is included. The largest discrepancy is that the $B(E2)$ value for the $\frac{1}{2}^-_1 \to \frac{5}{2}^-_1$ transition is an order of magnitude too large. One should bear in mind, however, that 10 parameters were used to reproduce the level properties of this nucleus.

In Fig. 7 we compare our results to the calculations of Vanden Berghe (branching ratios and mean lifetimes) and Van Hienen *et al.* ($\log ft$ values). Particularly interesting is the fact that the β decay to the $\frac{5}{2}^-_2$ level is about 5 times faster than that to the $\frac{5}{2}^-_1$ ground state. The calculation of Van Hienen predicts the ratio of the latter to the former to be 4×10^{-3}. Although Vanden Berghe does not present β-decay strengths, inspection of his wave functions shows that the $\frac{5}{2}^-_2$ level is predicted to have more accessible configurations than the $\frac{5}{2}^-_1$ level.

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