Structure of neutron-rich ^{74}Zn from ^{74}Cu decay and shell-model calculations for even-A Zn nuclei

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The first information on excited states in neutron-rich ^{74}Zn populated in the β decay of ^{74}Cu is presented. The ^{74}Cu half-life was measured to be 1.59 ± 0.05 s. On the basis of γ singles and coincidence measurements, a total of 19 γ rays were placed in a level scheme for ^{74}Zn with 10 excited states up to about 3 MeV. The low-lying level structure is satisfactorily reproduced by a shell-model calculation involving active protons in orbitals between the magic numbers 28 and 50 and neutrons filling the subshell between 38 and 50.

I. INTRODUCTION

Neutron-rich nuclei in the region near the doubly magic nucleus $^{78}_{28}Ni_{50}$ are of fundamental interest in determining the extent to which the known magic numbers are valid far from stability. In addition, the properties of these nuclei are of interest for astrophysical calculations since they lie at the beginning of the r-process path. Of particular interest are β decay half-lives and neutron binding energies.

Information on the very neutron-rich Zn nuclei ($A > 70$) is difficult to obtain, since the processes employed to produce the parent nuclei are fission and multinucleon transfer reactions for which the relevant cross sections for the neutron-rich Cu fragments are quite small. Recently Schmidt-Ott *et al.*[1] using 9 MeV/nucleon ^{76}Ge and 11.4 MeV/nucleon ^{82}Se on ^{nat}W targets observed small yields of ^{71}Cu, ^{72}Cu, and ^{73}Cu. Additionally, states in ^{74}Zn have been studied using the ^{76}Ge(^{14}C,^{16}O)^{74}Zn and ^{76}Ge(^{18}O,^{20}Ne)^{74}Zn two-proton pickup reactions.[2,3] Other than the ground state,[2,3] levels in ^{74}Zn at 0.67 and 1.84 MeV were observed.[2] This comprised the only information on excited states in ^{74}Zn prior to this work.

^{74}Cu was first observed in the thermal neutron fission of ^{235}U. Bernas *et al.*[4] observed $^{74-77}$Cu using the Lohengrin spectrometer and determined the relative yield of the various Cu nuclides, but no other properties of ^{74}Cu were determined. Lund *et al.*,[5] using the OSIRIS isotope-separator facility, observed $^{74-76}$Cu and ^{78}Cu. The half-life of ^{74}Cu was measured to be 1.60 ± 0.15 s and γ rays were observed at 606, 812, and 1138 keV, but no energy levels in ^{74}Zn were deduced.

An interesting parallel can be made between the systematics of the 2_1^+ states in Zn and Cd nuclei, since Zn has two protons beyond the magic number $Z=28$ and Cd has two proton holes in the magic $Z=50$ configuration. In the case of Cd, the 2_1^+ energy is nearly constant from ^{104}Cd through ^{112}Cd and then drops to a minimum at ^{118}Cd. This was interpreted[6] to be a minimum at the midpoint of a nearly degenerate $(1g_{7/2},2d_{3/2},1h_{11/2})$ neutron subshell. The 2_1^+ energy in the Zn system is roughly constant at around 1 MeV for $A=60-68$ but then decreases to 884 keV in ^{70}Zn and 652 keV in ^{72}Zn. A possible interpretation is that a nearly degenerate neutron subshell is being filled from $N=38$ to 50 composed of the $2p_{1/2}$ and $1g_{9/2}$ states. The midpoint of such a subshell would be at ^{74}Zn($N=44$). It is thus of interest to determine if the 2_1^+ level in the Zn isotopes reaches an energy minimum at ^{74}Zn and then rises as more neutron pairs are added.

Information on the spectroscopy of the neutron-rich nuclei in the $Z=28-32$, $A=68-76$ region is accumulating rapidly. A preliminary calculation for this region has been carried out with the code OXBASH (Ref. 7) using the proton-neutron formalism. Details of the assumptions used and results are given in Sec. IV. Several general questions were of concern in the present study: (1) How large a model space is necessary to adequately describe the known properties of these nuclei; (2) Are the systematics correctly predicted and understandable on general grounds? The predictions presented here can be viewed as preliminary to an effort to determine an effective shell-model interaction from least-squares fits to energy spectra for this region.

II. EXPERIMENTAL METHODS AND RESULTS

A. Source preparation

The sources of ^{74}Cu were obtained by fission of ^{235}U at the TRISTAN isotope-separator facility operating on line to the high-flux beam reactor at Brookhaven National Laboratory. In this work, a high-temperature plasma ion source[8] containing 4 g of enriched ^{235}U was exposed to a neutron flux of $3\times10^{10}n/\mathrm{cm}^2$ s. Beams of singly charged $A=74$ ions were mass separated and deposited on a movable aluminum-coated Mylar tape. Isotopes of Cu as well as Zn and Ga were observed in the $A=74$ beam. In addition, isotopes with $A=148$ were present due to the formation of doubly charged ions in the source. No evidence was observed for cross contamination from adjacent masses.

B. Measurements

Two HpGe γ ray detectors placed in 180° geometry viewed the source at the point where it was deposited on the tape. A thin plastic scintillator with approximately a 2π sr acceptance solid angle viewed the source, and the resulting signals served both as a beam monitor and a β gate for the singles spectra. This background suppression technique was necessary due to the low fission yield at $A=74$. The primary data for the decay of short-lived ^{74}Cu was obtained in a run lasting 4.5*d* in which the beam was collected and data accumulated for 3 s followed by movement of the tape and repetition of the cycle in order to minimize contributions from long-lived activities. Several other runs involving enhancement of the longer-lived ^{74}Zn and ^{74}Ga activities were also carried out. By comparison of the relative intensity of γ rays in the various spectra, it was possible to identify γ transitions due to the decay of ^{74}Cu.

Singles and coincidence γ ray measurements were carried out simultaneously covering an energy range of 0.02–5.0 MeV and γ rays from ^{74}Cu decay were observed up to almost 2.4 MeV. The γ ray energies were calibrated using intense well-known lines from $^{73}\mathrm{Ge}(n,\gamma)^{74}\mathrm{Ge}$ and ^{148}La decays.[9,10] The efficiency of each detector was determined using standard sources in the same geometry as for the $A=74$ runs.

γ-γ coincidence events were recorded as address triplets representing γ ray energies and their time separation. The fast coincidence system used standard time-to-amplitude conversion. A total of 1.3×10^6 γ-γ coincidence events were recorded but only a small fraction were from ^{74}Cu decay. The time resolution was 20 ns at full width at half maximum (FWHM).

C. Half-life

The half-life of ^{74}Cu was determined in a special run cycle in which the beam was collected on the tape for 6 s and then deflected for 6 s. The tape was then moved and the cycle repeated. During the run, 24 β gated γ singles spectra were sequentially recorded at 0.5 s intervals. The run lasted for 10 h and only the decay portion of the cycle was used for the half-life determination. The decay curve for the intense 605-keV γ ray is shown in Fig. 1. Our result of 1.59 ± 0.05 s is in excellent agreement with the value of 1.60 ± 0.15 s measured by Lund *et al.*[5]

Since ^{74}Cu is the most neutron-rich member of the $A=74$ decay chain known, it provides a test of half-life predictions of the older gross theory of Takahashi, Yamada, and Kondoh[11] and the more recent work of Klapdor, Metzinger, and Oda[12] in which structures in the β strength function have been taken into account. The more recent predictions are systematically shorter than the gross theory predictions for neutron-rich nuclei. For ^{74}Cu the gross theory predictions range from about 2.5 to 5.5 s depending upon the form assumed for the single-particle strength function, thus overestimating the half-life. The more recent calculations predict a value of 0.69 s which underestimates the half-life.

D. γ ray energies, intensities, and coincidence relationships

A typical β gated γ singles spectrum is shown in Fig. 2 for the energy range from 0.02 to 2.4 MeV. The inset in Fig. 2 is discussed in detail in the next section. In Fig. 3 the γ ray spectra in coincidence with the 605- and 1064-keV γ rays are shown.

The γ energies, relative intensities, placements, and coincidence relationships are summarized in Table I. The uncertainties associated with the energies are due to statistical uncertainties in determining peak centroids and system nonlinearities, while the uncertainties associated with the relative intensities reflect uncertainties in the determination of peak areas and detector efficiencies. Corrections for coincidence summing were made to correct the relative intensities for the close geometry and high efficiencies of the detectors. There is also the possibility for a significant intensity of γ rays below the present detection limits.

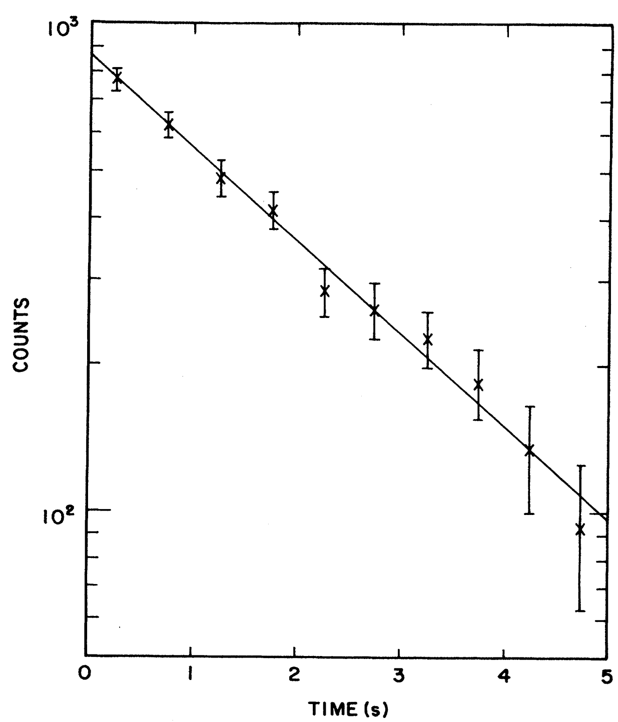

FIG. 1. Decay curve for the 605-keV γ ray following the decay of ^{74}Cu. The line represents a fit to the data with a half-life of 1.59 ± 0.05 s.

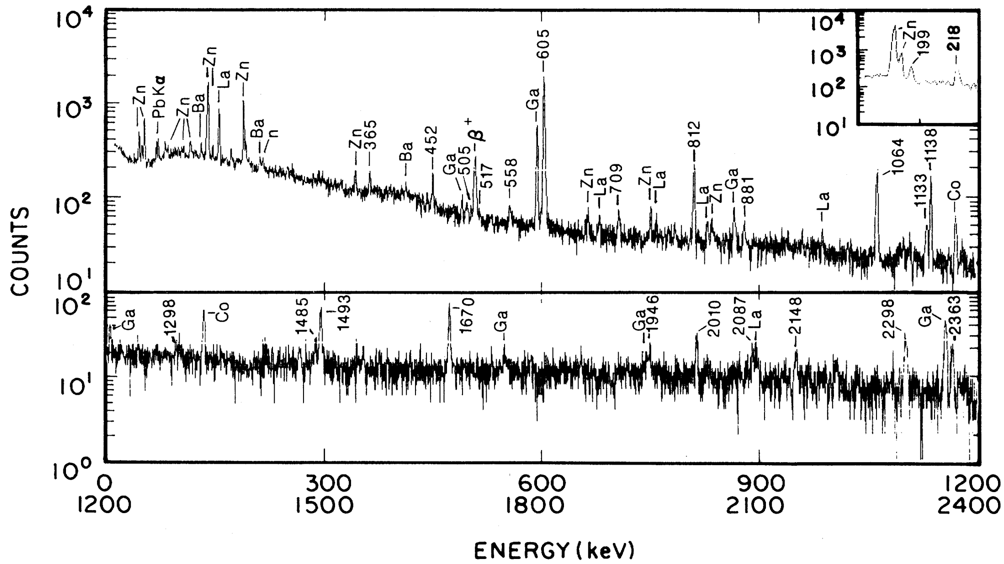

FIG. 2. γ ray singles spectrum from the decay of a mass 74 source with a data collection cycle set to emphasize short half-lives. Lines assigned to the decay of ^{74}Cu are labeled with their energies in keV. Other members of the $A = 74$ decay chain are labeled Zn and Ga. Lines from the $A = 148$ decay chain (from doubly charged ions) are labeled Ba and La and two lines from ^{60}Co are labeled Co. The peak at 218 keV labeled *n* in the main spectrum, is a candidate for a γ ray from ^{73}Zn decay following delayed-neutron emission from ^{74}Cu. (See Sec. II E.)

E. Possible delayed-neutron emission from ^{74}Cu

Delayed neutrons have not been observed in the $A = 74$ chain, but the recent mass calculation of Möller and Nix[13] predict delayed-neutron emission to be energetically possible in ^{74}Cu with a "window" of 1.74 MeV. All calculations predict ^{74}Zn to be stable against delayed-neutron emission.

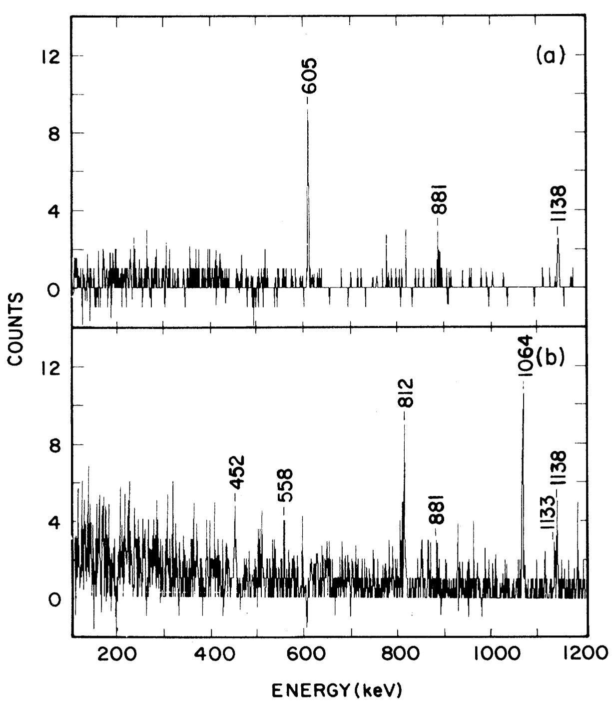

FIG. 3. Spectra of γ rays in coincidence with the (a) 1064-keV and (b) 605-keV γ rays, respectively. The Compton background has been subtracted.

A search was made for evidence of delayed-neutron emission from ^{74}Cu in our γ ray spectrum. The decay of ^{73}Cu has been studied by Runte *et al.*,[14] but no γ rays reported in their study (in particular the strong γ ray at 449 keV) could be assigned to ^{74}Cu decay. A γ ray at 199 keV, observed[14] in ^{73}Cu decay, had a half-life much longer than that of ^{74}Cu, so it cannot result from delayed-neutron emission from ^{74}Cu. A γ ray was observed in this work at 218.6$\pm$0.2 keV, in fair agreement with an energy of 218.1$\pm$0.2 keV reported[14] to be the strongest transition in the decay of 23.5 s ^{73}Zn. The above γ rays are shown in the insert to Fig. 2 which displays data from a time cycle in which the longer-lived activities were enhanced. The decay curve observed in this work for the 218-keV transition is consistent with the buildup of ^{73}Zn activity from the decay of ^{74}Cu through delayed-neutron emission but the statistics are poor, thus some weak evidence for the delayed-neutron decay of ^{74}Cu has been obtained.

III. THE ^{74}Cu DECAY SCHEME

The level scheme for ^{74}Zn populated in ^{74}Cu decay is shown in Fig. 4. This scheme is based on the γ ray singles and coincidence measurements presented here. Since Cu ions comprised a small fraction of the $A = 74$ beam, it was not possible to measure the ground-state β feeding. However, logft calculations have been made assuming zero ground-state β feeding. The model basis for this assumption is discussed in the next section. The Q_β of 7.36

TABLE I. γ transitions observed in ^{74}Cu decay.

E_γ (keV)	I_γ[a]	Placement (keV)	Coincident[b] γ rays (keV)
365.86±0.23	2.1±0.3[c]	unplaced	
452.59±0.12	4.7±0.4	2551-2099	605,(1493)
505.3±0.6	0.8±0.4	1670-1163	
517.2±0.5	0.6±0.3	2616-2099	
558.21±0.22	1.7±0.4	1163-605	605
605.80±0.05	100.0±2.0	605-0	452,558,812 (881),1064, 1133,1138,2010, (2299),(2363)
709.5±0.4[d]	3.7±1.3[d]	2808-2099	
812.61±0.09	16.3±0.5	1418-605	605,(1133) (1485)
881.71±0.17	2.4±0.4	2551-1670	605,1064
1064.35±0.06	21.2±1.6	1670-605	605,(881),1138
1133.05±0.24	4.2±0.6	2551-1418	605
1138.79±0.08	18.6±1.0	2808-1670	605,1064,1670
1298.9±0.4	1.3±0.4	2969-1670	
1485.9±0.3	2.6±0.5	2904-1418	(812)
1493.36±0.15	10.7±1.5	2099-605	452,605
1670.23±0.10	10.2±1.9	1670-0	1138
1946.2±0.3	2.3±0.5	2251-605	
2010.52±0.23	5.0±0.7	2616-605	(605)
2087.8±0.5	2.5±0.7[c]	unplaced	
2148.1±0.3	3.3±0.7[c]	unplaced	
2298.75±0.24	7.4±0.9	2904-605	(605)
2363.3±0.3	5.4±1.1	2969-605	(605)

[a]Normalized to 100 for the intensity of the 605-keV γ ray. If zero β branching to the ^{74}Zn ground state is assumed the absolute γ ray intensity per 100 decays is obtained by multiplying I_γ by 0.91.
[b]Possible coincidences are indicated in parentheses.
[c]Not corrected for possible coincidence summing.
[d]May be a doublet.

MeV used for logft calculations was obtained from calculations discussed in the next section. This value is less than that of 9.67 MeV from the tables of Möller and Nix.[13] Under the above assumptions the resulting logft values are given in Fig. 4 and are assumed to have an error of ±0.2 or less. In Fig. 4, β feedings and logft values are not shown for levels with β feedings of less than 2%. The levels observed in this work are discussed below and are compared with the results of a large-space shell-model calculation in the next section.

A. ^{74}Cu ground state

J^π for the ground state of ^{74}Cu is determined by coupling the 29th proton to the 45th neutron. From systematics of odd-A nuclei and simple shell-model considerations it is expected that the odd proton would be in the $1f_{5/2}$ or $2p_{3/2}$ orbit while the odd neutron would be in the $2p_{1/2}$ orbit. These couplings would result in positive parity for the ^{74}Cu ground state. This is consistent with the low logft values observed from β decay to low-lying levels in ^{74}Zn. In particular the logft of 5.4 to the 2_1^+ state in ^{74}Zn supports positive parity for the ^{74}Cu ground state. On the basis of calculations of level energies presented in the next section, we predict $J^\pi=3^+$ from $\pi 1f_{5/2}\otimes\nu 2p_{1/2}$ for the ^{74}Cu ground state. This would imply that ^{74}Cu decays primarily to $J^\pi=2^+$, 3^+, and 4^+ states in ^{74}Zn. An alternate interpretation would be that the ^{74}Cu ground state has $J^\pi=1^+$ from $\pi 2p_{3/2}\otimes\nu 2p_{1/2}$. In that case ^{74}Cu would decay primarily to $J=0^+$, 1^+, and 2^+ states in ^{74}Zn and β decay to the ^{74}Zn ground state could not be neglected. (A 2^+ assignment for the ^{74}Cu ground state is excluded by β decay selection rules if the level at 1418 keV has $J^\pi=0^+$ or 4^+.)

B. Levels in ^{74}Zn below 2 MeV

We present here the first information on excited states in ^{74}Zn obtained from decay studies. Pickup reactions have been used previously to study states in ^{74}Zn. Haupt *et al.*[3] measured the mass of ^{74}Zn using the (^{18}O,^{20}Ne) reaction but only observed the ground state. Bernas *et al.*[2] used the (^{14}C,^{16}O) reaction and observed excited states at 0.67±0.03 and 1.84±0.05 MeV but were unable to determine their J^π due to poor statistics and channel coupling effects.

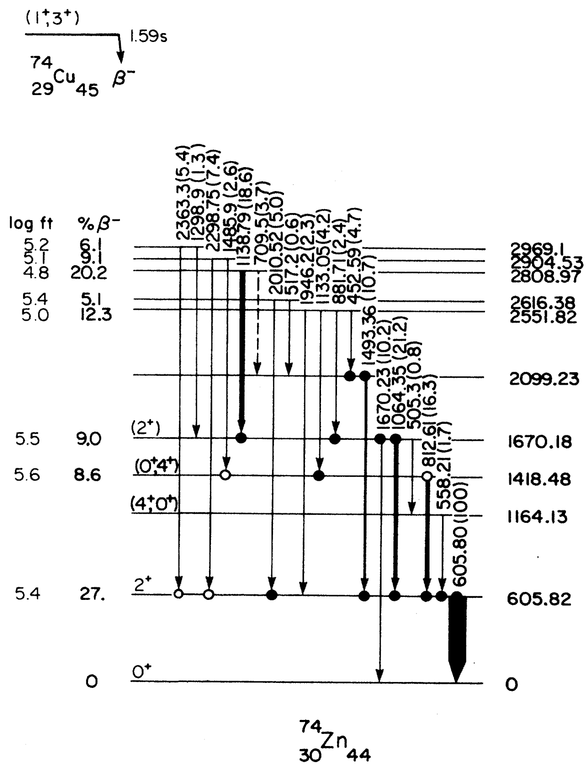

FIG. 4. Decay scheme for ^{74}Cu. All energies are in keV. The logft values were calculated assuming no β^- feeding to the ^{74}Zn ground state. If the ^{74}Cu ground state is 1^+ then 1164- and 1418-keV levels would be 4^+ and 0^+, respectively, but if the ^{74}Cu ground state is 3^+ then the 1164- and 1418-keV levels would be 0^+ and 4^+, respectively.

The first-excited state at 605 keV is postulated to be 2^+ based on systematics. The energy fits well with the systematics of the neutron-rich even-A Zn isotopes. The level is well established by numerous coincidences and the fact that the depopulating γ ray at 605 keV is by far the strongest observed. This state probably corresponds to the one observed in the (^{14}C,^{16}O) reaction[2] at 0.67±0.03 MeV.

A triplet of states is observed at 1164, 1418, and 1670 keV, all states being well established by energy sums and coincidences. The 1670-keV level is the best candidate for the 2_2^+ level since it is the only one of the triplet decaying to the ground state. The level at 1418 keV is strongly fed in β decay and is thus the best candidate for the 4_1^+ state if the ^{74}Cu ground state is assumed to be 3^+. On the same basis the level at 1164 keV has very little β feeding and is thus the best candidate for the 0_2^+ state, since the β feeding could easily become zero due to possible γ feeding from high-lying unobserved levels which might populate the 1164-keV level in ^{74}Zn. If a J^π of 1^+ is assumed for the ^{74}Cu ground state, the roles of the 1164- and 1418-keV levels would be reversed. The above assignments are based on systematics and decay patterns.

The logft values for the 2_1^+, 2_2^+, and 1418-keV levels are all ≤ 5.6, consistent with the interpretation of allowed β feeding from a 3^+ or 1^+ state. It is not clear whether a level observed[2] in the (^{14}C,^{16}O) reaction at 1.84±0.05 MeV corresponds to any level observed in this work.

C. Levels in ^{74}Zn between 2 and 3 MeV

A cluster of five levels is postulated between 2.5 and 3 MeV. Of the β feeding observed in this work, 52% goes to these levels. It is not possible to accurately draw correspondences between these levels and the results of the shell-model calculation but the concentration of β strength is striking. The model calculation for the ^{74}Cu ground state indicates the unpaired neutron to be in the $2p_{1/2}$ orbit almost 100% of the time and the excited states in ^{74}Zn have considerable $2p_{3/2}$ and $2p_{1/2}$ components. Thus the $\nu p_{1/2} \rightarrow \pi p_{1/2}$ and $\nu p_{1/2} \rightarrow \pi p_{3/2}$ allowed β transitions are probably responsible for most of the concentration of β strength observed between 2.5 and 3.0 MeV.

IV. SHELL-MODEL CALCULATIONS FOR THE NEUTRON-RICH Zn REGION

A. The interaction

The present calculation is a first step toward the ultimate goal of obtaining an effective shell-model interaction for this region using least-squares fits to energy spectra. The calculation was performed with the code OXBASH.[7] The proton model space was taken to be $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, $1g_{9/2}$ outside a closed $1f_{7/2}$ $Z=28$ core. The neutron space was taken to be $2p_{1/2}$, $1g_{9/2}$ outside a closed $1f_{7/2}$, $1f_{5/2}$, $2p_{3/2}$ $N=38$ core. Thus the core was assumed to be ^{66}Ni and binding energies were relative to that nucleus. Delfini and Glaudemans[15] have shown that the closure of the $1f_{7/2}$ shell for $Z>28$ nuclei is a quite valid assumption; however, closure of the $1f_{5/2}$, $2p_{3/2}$ subshells at $N=38$ is certainly not a good assumption near $A=66$. For instance, the ^{66}Ni first-excited state lies at 1425 keV.[16] However, it is assumed here that as N increases above 38 these subshells fall rapidly below the Fermi surface and soon become of minor importance.

For the protons, the Ji-Wildenthal interaction[17] constructed for the same proton model space as here, but for $N=50$ isotones, was used as a start. However, the single-particle energies (SPE) that they derived for a ^{78}Ni core were not appropriate for a ^{66}Ni core. This is expected because of the difference in neutron occupancy of the $2p_{1/2}$, $1g_{9/2}$ subshells. Our approach was to find the best set of SPE for the $A=66$ region by consideration of the spectra of $^{67-69}$Cu and $^{68-69}$Zn. It was then assumed that these SPE vary linearly with N ending at the Ji-Wildenthal values at $N=50$. In performing these calculations it was found that the Ji-Wildenthal interaction was too strong for the $A \approx 66$ region. Better fits were obtained by multiplying the Ji-Wildenthal proton two-body matrix elements (TBME) by 0.7.

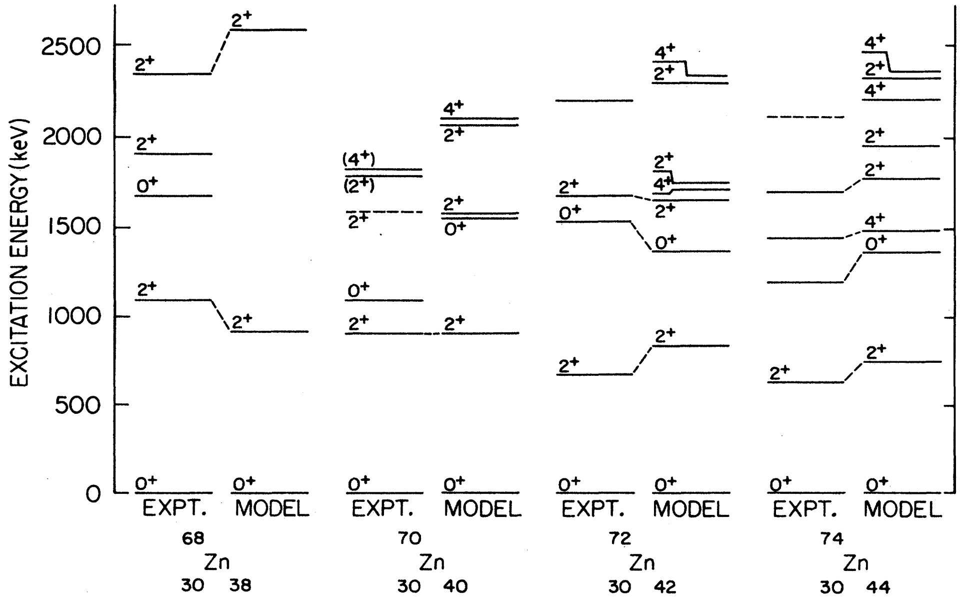

FIG. 5. Comparison of predicted and experimental $J^\pi=0^+$, 2^+, and 4^+ levels of ^{68,70,72,74}Zn. All predicted 0^+, 2^+, 4^+ levels below 2.4-MeV excitation are shown. Possible correspondences between predicted and experimental levels are indicated by dashed lines.

The neutron-neutron and proton-neutron interactions are hybrids. Initially, the necessary TBME were generated from the bare G-matrix potential of Hosaka *et al.*,[18] then the pn and nn TBME involving the $2p_{1/2}$, $1g_{9/2}$ subshells were replaced by a modification by Brown[19] of the "seniority-fit total-energy" TBME of Serduke, Lawson, and Gloeckner.[20] As for the protons, it was found that the neutron SPE appropriate for the $A=90$ region (where this neutron interaction was designed to work) are not suitable for the $A=68$ region. Consequently, the two neutron SPE were chosen to fit the binding energies of the first $\frac{1}{2}^-$ and $\frac{9}{2}^+$ states of ^{69}Zn, and then assumed to vary linearly with proton number from $Z=28$ to 40 (where they were previously determined for the $A\approx 90$ region). A listing of the SPE and TBME is available from one of the authors (E.K.W.).

B. Spectra and binding energies

The $J^\pi=0^+$, 2^+, and 4^+ spectra of ^{68,70,72,74}Zn are compared to experiment in Fig. 5. From this figure it appears that the predictions get better as N increases. This is the expected consequence of neglecting excitations of the neutron $1f_{5/2}$, $2p_{3/2}$ subshells. To illustrate this point, the ^{68}Zn spectrum was calculated with the van Hees interaction[21] and a model space of $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$ for both protons and neutrons. The first 0^+ and 2^+ levels were both found to be composed predominantly of wave function components with either one or two neutrons promoted from the $1f_{5/2}$, $2p_{3/2}$ subshells into the $2p_{1/2}$ shell. As remarked above, it is expected that excitations of the $1f_{5/2}$, $2p_{3/2}$ subshells will rapidly become unimportant as N increases.

Although experimental information on Zn nuclides with $A\geq 70$ is sparse, it is interesting to compare the available information with the calculations discussed above. Reasonable agreement is observed for 0^+, 2^+, and 4^+ states up to about 2 MeV. However, the trend of decreasing energy with increasing A for the 2_1^+ states starting at $A=70$ is not adequately reproduced. In Table II the composition of the major components of the calculated wave functions for the 0_1^+, 2_1^+, 0_2^+, 2_2^+, and 4_1^+ states in ^{74}Zn are given. The major occupancy for the protons is in the $1f_{5/2}$ and $2p_{3/2}$ orbits while the neutrons are shared between the $2p_{1/2}$ and $1g_{9/2}$ orbits (due to restriction of the model space).

Calculated binding energies for neutron-rich Ni, Cu, and Zn nuclides are compared to experiment in Table III. The agreement is very good and, we believe, gives the most accurate available predictions for the unmeasured masses of Cu and Zn isotopes. For the masses calculated here, the average deviation (defined as absolute value of experiment[22] minus theory) is 342 keV as compared to an average deviation of 573 keV using the Möller-Nix mass formula.[13] The results provide useful estimates for the Q_β values for decay of the $A=72-74$ Cu isotopes.

The results for the odd-odd Cu isotopes have two failings. First, for all four nuclides considered, the ground state is predicted to have odd parity with even-parity levels commencing 50–300 keV higher, while experimentally the ground states are all known to have even parity. In the case of ^{74}Cu, a 2^-, 3^- doublet is predicted to lie 280 keV below the first even-parity (3^+) level. Second, for ^{68,70,72}Cu (all known to have $J^\pi=1^+$ ground states) a 2^+ level is calculated to lie lower than the 1^+ state (by 129, 78, and 22 keV, respectively; see Fig. 6 for ^{68}Cu). It should be noted that the same 2^+-1^+ inversion is found

TABLE II. Composition of ^{74}Zn wave functions for 0^+, 2^+, and 4^+ states below 2.2 MeV. (No 1^+, 3^+, or negative-parity states were found in the calculation below 2.2 MeV.)

State (J^π)	Energy (keV)	Occupation[a] (%)	Protons $1f_{5/2}$	Protons $2p_{3/2}$	Protons $2p_{1/2}$	Protons $1g_{9/2}$	Neutrons $2p_{1/2}$	Neutrons $1g_{9/2}$
0_1^+	0	33.3		2			2	4
		20.6	2					6
		13.6	2				2	4
		7.3		2				6
2_1^+	726	31.6		2			2	4
		15.8	2					6
		10.7		1	1		2	4
		10.2	2				2	4
		8.2	1	1			2	4
0_2^+	1346	51.0	2					6
		32.8		2			2	4
4_1^+	1454	22.9		2			2	4
		20.3	1	1			2	4
		15.1	2					6
		11.0	1	1				6
		8.6	2				2	4
		8.4		1	1		2	4
2_2^+	1744	48.5	2					6
		26.3		2			2	4
		7.1	1		1			6
4_2^+	2187	44.9		2			2	4
		18.2	2					6
		9.1	1	1			2	4
		9.0	1	1				6

[a]Only wave function components greater than 7% are included.

for ^{68}Cu with the van Hees interaction.[21] Neither of these defects is considered to be serious since the energy differences are small and could be remedied by small adjustments of the relevant TBME.

Of particular interest to the present study is the predicted spin of the lowest even-parity state of ^{74}Cu. As N increases from 38 to 50, the relative $\pi 1f_{5/2}$-$\pi 2p_{3/2}$ energy gap changes from about 2100 keV, as determined by our consideration of the $A=67-69$ region, to -1153 keV, as determined by the least-squares fit of Ji and Wildenthal.[17] This is likely to be a consequence of the greater overlap of $\pi 1f_{5/2}$ with $\nu 1g_{9/2}$. Experimentally all known odd-A Cu isotopes have $J^\pi=\frac{3}{2}^-$ for the ground state. However, at $N=50$ $J^\pi=\frac{5}{2}^-$ for ^{81}Ga,[23] while $J^\pi=\frac{3}{2}^-$ for ^{85}Br and ^{87}Rb, implying that the $f_{5/2}$ states cross before $N=50$ is reached. Therefore, at some point the $J^\pi=3^+$ level of $\pi 1f_{5/2}\otimes\nu 2p_{1/2}$ will fall below the $J^\pi=1^+$ level of $\pi 2p_{3/2}\otimes\nu 2p_{1/2}$. The prediction is for this to occur for ^{74}Cu at which the 1^+ level is calculated to lie 232 keV above the 3^+ level (see Table III). However, small adjustments of the TBME can shift the N value for which the 3^+ falls below the 1^+ level. Both possibilities for the ^{74}Cu ground state are discussed below.

C. β and γ decays

A Gamow-Teller decay with $\log ft=5.0$ is just about the weakest that can be expected for a well-tuned shell-model interaction to predict accurately. The decays of ^{74}Cu are weaker, thus quantitative comparison of the predicted rates to experiment is pointless. We only note that for a ^{74}Cu ground state of either $J^\pi=1^+$ or 3^+, the average strengths of the β decay is in rough accord with experiment. The weakness of the decays is mainly due to the small spatial overlap in subshells between the neutrons and protons and the $\Delta l=0$ selection rule for allowed decays.

The electric quadrupole properties of nuclei are dependent on rather general features and are always instructive to consider. Model predictions for some $E2$ transitions in ^{74}Zn are collected in Table IV. From the energy spectrum of ^{74}Zn one would consider it possible that the nucleus had vibrational properties, i.e., the 0_2^+, 2_2^+, and 4_1^+ levels are closely spaced at about twice the energy of the 2_1^+ level. However, the experimental relative $B(E2)$ values from the 2_2^+ level indicate a nonvibrational character, since the 2_2^+ decays preferentially to the $(4^+,0^+)$ level at 1164 keV. The calculated $E2$ rates of Table IV confirm the fact that ^{74}Zn is not even remotely vibrational. Nor do the predicted $E2$ rates show the pattern of a rotational nucleus, rather they are generally what is expected for mildly collective shell-model states.

Although half-lives have not been determined for any excited states in ^{74}Zn, the 2_2^+ level was observed to deexcite to the 0_1^+ and 2_1^+ states and the level at 1164 keV; therefore calculated $B(E2)$ ratios can be compared with

TABLE III. Comparison of experimental and calculated nuclear binding energies for $A=67-74$ Ni, Cu, and Zn isotopes.

Nucleus	J^π	Binding energy (keV)[a] experiment	model	Δ(model-expt)
^{67}Ni	$\frac{1}{2}^{-\,b}$	5 786	5 149	−637
^{68}Ni	0^+	13 597	13 790	+193
^{69}Ni	$\frac{9}{2}^{+\,b}$	18 647	19 310	+663
^{68}Cu	1^+	14 887	14 673	−214
	3^+		12 094	
^{70}Cu	1^+	28 457	28 841	+384
	3^+		28 310	
^{72}Cu	1^+		42 585	
	3^+		42 355	
^{74}Cu	3^+		56 106	
	1^+		55 874	
^{67}Cu	$\frac{3}{2}^-$	8 564	8 883	+319
^{69}Cu	$\frac{3}{2}^-$	23 144	23 267	+123
^{71}Cu	$\frac{3}{2}^-$	36 367	37 147	+780
^{73}Cu	$\frac{3}{2}^{-\,b}$		50 759	
^{68}Zn	0^+	18 556[a]	18 557[a]	+1
^{70}Zn	0^+	34 253	33 670	−583
^{72}Zn	0^+	48 969	48 416	−553
^{74}Zn	0^+	62 686[c]	62 686[c]	+0
^{69}Zn	$\frac{1}{2}^-$	25 038	25 041	+3
	$\frac{9}{2}^+$	24 599	24 600	+1
^{71}Zn	$\frac{1}{2}^-$	40 086	39 671	−415
	$\frac{9}{2}^+$	39 928	39 569	−359
^{73}Zn	$\frac{1}{2}^-$	54 317	54 074	−243
	$\frac{9}{2}^+$		54 105	

[a]Binding energy in excess of that for ^{66}Ni (576 833 keV). A small final iteration was made by adding a constant to the SPE in order to reproduce the experimental binding energy of ^{68}Zn.
[b]J^π of ground state not certain from experiment and thus based on the calculation.
[c]The prefect agreement here is accidental and the results were not normalized to obtain the values given.

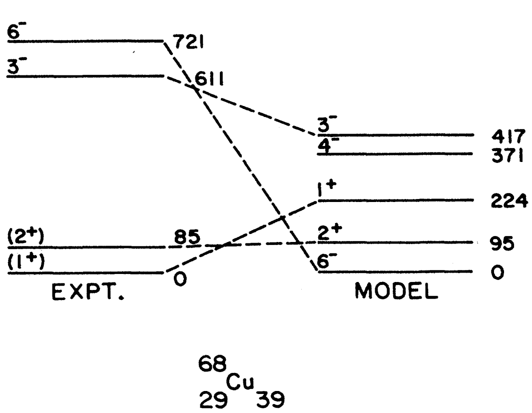

FIG. 6. Calculated low-lying level structure for ^{68}Cu.

TABLE IV. Calculated $B(E2)$ transition rates between even-parity states of ^{74}Zn

$J(\#)\rightarrow J(\#)$	(W.u.)[a]
2(1)→ 0(1)	8.9
4(1)→ 2(1)	19.7
6(1)→ 4(1)	10.3
8(1)→ 6(1)	11.5
10(1)→ 8(1)	13.0
12(1)→10(1)	7.9
0(2)→ 2(1)	0.021
2(2)→ 4(1)	0.10
2(2)→ 2(1)[b]	0.0058
2(2)→ 0(1)	0.0062
2(2)→ 0(2)	7.1

[a]The $B(E2)$ values are in Weisskopf units (1 W.u.$=18.455$ e^2f^4). The effective charges used were $e_p=1.5e$ and $e_n=0.5e$.
[b]The $B(M1)$ for this transition is 0.049 Weisskopf units.

the experiment. The transition probability ratio $\lambda(2_2^+ \rightarrow 1164)/\lambda(2_2^+ \rightarrow 0_1^+)$ was measured to be 0.088 ± 0.04. If the 1164-keV level is assumed to be the 0_2^+ state then the above ratio is calculated to be 3, but if the state is assumed to be 4_1^+ then the ratio is calculated to be 0.04. Thus the $B(E2)$ calculation favors a 4_1^+ assignment for the 1164-keV level whereas comparison of the calculated and experimental energy spectra favors the 0_2^+ assignment.

The ratio $\lambda(2_2^+ \rightarrow 2_1^+)/\lambda(2_2^+ \rightarrow 0_1^+)$ has a measured value of 2.1 ± 0.4. If only $E2$ transitions are assumed, then the ratio is predicted to be 0.1 but if the calculated $M1$ contribution to $\lambda(2_2^+ \rightarrow 2_1^+)$ is added, then this ratio increases to 1.0×10^3. The calculation thus indicates that the $M1$ contribution dominates the $2_2^+ \rightarrow 2_1^+$ transition, whereas experiment indicates more comparable $M1$ and $E2$ strengths. Either the calculated $M1$ strength is too large for the $2_2^+ \rightarrow 2_1^+$ transition or the calculated $E2$ strength is too weak for the $2_2^+ \rightarrow 2_1^+$ and $2_2^+ \rightarrow 0_1^+$ transitions. To summarize the calculated $E2$ strengths indicated the J^π choices shown on the left-hand side of the parentheses in Fig. 4 whereas the calculated energy levels favor the J^π choices on the right-hand side.

V. CONCLUSIONS

In this paper we have presented the first detailed information on the decay of ^{74}Cu and the level structure of ^{74}Zn. In ^{74}Zn a total of 10 excited states up to almost 3 MeV was observed. Superficially ^{74}Zn appears to be a vibrator with a triplet of states at about twice the energy of the 2_1^+ state but both the experiment and the calculation predict the states to be shell-model like with a mildly collective character. Half of the observed β intensity goes to a group of five states between 2.5 and 3.0 MeV. These β transitions are probably allowed and consist primarily of transitions between $p_{1/2}$ and $p_{3/2}$ states.

Shell-model calculations of the even-A neutron-rich Zn isotopes were carried out with the active protons in the $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1g_{9/2}$ shells, but the neutrons were confined to the $2p_{1/2}$ and $1g_{9/2}$ shells. Reasonable agreement is obtained between experiment and the calculation for states below 2.0 MeV in excitation energy. The calculated proton strength for states below 2.2 MeV in ^{74}Zn is almost entirely in the $1f_{5/2}$ and $2p_{3/2}$ orbits.

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