Structure of ^{76}Zn from ^{76}Cu decay and systematics of neutron-rich Zn nuclei

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The first postulation of excited states in neutron-rich ^{76}Zn is presented. We postulate the levels in ^{76}Zn to be populated by high- and low-spin isomers of ^{76}Cu with half-lives of 0.57 s and 1.27 s, respectively. Of 12 γ rays attributed to ^{76}Zn decay, 11 are placed in a level scheme for ^{76}Zn with eight excited states up to 3 MeV. A shell-model calculation has been carried out to reproduce the systematics of the neutron-rich Zn isotopes up to A=76. The model space involves active protons in orbitals between Z=28 and 50 and neutrons in orbitals filling the subshell between N=38 and 50.

I. INTRODUCTION

It is of fundamental interest to study the properties of nuclei near $^{78}_{28}$Ni$_{50}$ to determine to what extent the magic numbers determined near stability are valid for very neutron-rich regions. The properties of nuclei in this region are also of interest for astrophysical calculations since they lie at the beginning of the r-process path.

It is difficult to obtain information on Zn nuclei with $A > 74$ since stable nuclei are not available to use as targets for simple transfer reactions. Therefore, information on the structure of $A > 74$ Zn nuclei must be obtained by studying the decay of $A > 74$ Cu nuclei. Cu nuclei with $A > 74$ were first observed in the thermal neutron fission of ^{235}U. Bernas *et al.*[1] observed $^{74-77}$Cu using the Lohengrin spectrometer and determined the yield of ^{76}Cu to be 7×10^{-8} per fission. Using the OSIRIS separator, Lund *et al.*[2] observed $^{74-76,78}$Cu and reported a half-life of 0.35 ± 0.08 s and γ rays at 598, 697, and 947 keV for ^{76}Cu. Reeder *et al.*[3] observed delayed neutron activity at A=76 which they ascribed to ^{76}Cu. The half-life was measured to be 0.61 ± 0.10 s and the delayed neutron emission probability P_n was measured to be $3 \pm 2\%$. Prior to the present study, no excited states had been postulated[1-4] for ^{76}Zn or any Zn nuclide with $A > 74$.

The excitation energy of the 2_1^+ state for Zn isotopes remains rather constant at about 1 MeV as neutrons fill the $(1f_{5/2}, 2p_{3/2})$ subshell (N=28 to 38) but then rapidly decreases in energy as the $(1g_{9/2}, 2p_{1/2})$ subshells fill, reaching a minimum[5] of 605 keV for ^{74}Zn. A similar situation exists for the 2-proton hole states (in Fe isotopes) where the excitation energy of the 2_1^+ state is approximately constant at 0.85 MeV as the $(1f_{5/2}, 2p_{3/2})$ subshell fills. If the decrease in the 2_1^+ energy for Zn nuclei is an effect of the filling of the $(1g_{9/2}, 2p_{1/2})$ subshells, one might expect the 2_1^+ energy to reach a minimum for ^{74,76}Zn, since this is the $g_{9/2}$ mid-subshell region, and then increase as N=50 is approached.

We have undertaken the study of the structure of ^{76}Zn to determine the behavior of the low-lying states as the $(1g_{9/2}, 2p_{1/2})$ neutron subshells are filled. The experimental results and resulting decay scheme are presented in Sec. II and III. The results are compared in Sec. IV with a shell-model calculation and the systematics of the region are discussed. Preliminary results from this study have been given at conferences.[6]

II. EXPERIMENTAL METHODS AND RESULTS

A. Source preparation

The sources of ^{76}Cu were obtained using a high-temperature plasma ion source[7] containing 4 g of enriched ^{235}U in a thermal neutron flux of $3 \times 10^{10} n/\mathrm{cm}^2\,\mathrm{s}$ from the High-Flux Beam Reactor at Brookhaven National Laboratory. The A=76 beam was mass-separated using the TRISTAN on-line mass separator. The beam of mass-separated ions was deposited on a movable aluminum-coated Mylar tape. Isotopes of Cu, Zn, and Ga were observed in the A=76 beam, but there was no evidence for cross contamination from adjacent masses. Also, no γ rays were observed from nuclides that would be present due to acceleration of doubly charged A=152 ions.

B. Measurements

The source was viewed at the deposit point, "parent port," using two HpGe γ ray detectors in 180° geometry. In addition a HpGe and LEPS γ ray detector in 180° geometry viewed the source at a point, "daughter port," downstream from the parent point. All detectors were β gated using thin plastic scintillators. The background suppression provided by the β coincidences was necessary due to the low intensity of the A=76 beam.

The presence of ^{76}Cu in the beam was first established in a 3-h survey run. Next a special run lasting 35 hours, described in Sec. II C, was made to determine the ^{76}Cu half-life. The measured half-life was used to set the parameters for the main run which lasted 4.7 days. In the main run the beam was deposited on the tape for 1.5 s, moved to a point halfway between the parent and daughter ports, and the cycle repeated. Comparison of spectra from the parent and daughter ports along with known information from ^{76}Zn and ^{76}Ga decay allowed us to make assignments for all γ rays of significant intensity.

Singles and coincidence γ-ray measurements were carried out simultaneously, covering an energy range from 0.01 to 4 MeV. A calibration run using the A=76 beam and a standard source containing ^{125}Sb, ^{154}Eu, and ^{155}Eu was used to establish a set of ^{76}Zn secondary energy standards that were used in turn to establish the energy nonlinearity for the spectra from the long A=76 run. The calibration was extended to higher energies using known lines from ^{76}Ga decay. The efficiency for the detectors was established using a standard source in the run geometry. γ–γ coincidence events were recorded as address triplets representing γ-ray energies and their time separation. The system used standard time-to-amplitude conversion with a time resolution of 20 ns full width at half maximum.

C. Half-life

The ^{76}Cu half-life was measured in a separate run in which the A=76 beam was collected on the tape for 1.0 s and then electrostatically deflected for 1.5 s. The tape was then moved and the cycle repeated. During the run, 25 β gated γ-ray singles spectra were sequentially recorded at 0.1 s intervals. Only the decay portion of the cycle was used to determine the ^{76}Cu half-life.

Decay curves for the 598- and 697-keV γ rays are shown in Fig. 1. The half-lives were measured to be 0.84 ± 0.06 s and 0.57 ± 0.06 s, respectively. Since these two γ rays are observed to be in strong coincidence with each other, it was concluded that two isomers of ^{76}Cu were present. We postulate that the 0.57 s half-life was due to the decay of an isomer, probably with $J = 3 - 5$, that directly β decays to a level at 1296 keV, which in turn decays by emission of the 697-keV γ ray. We postulate a first-excited state at 598 keV that is directly β fed by a low-spin ($J = 1 - 3$) isomer of ^{76}Cu and indirectly fed by the high-spin isomer. A point-by-point subtraction was made in the 598-keV decay curve to account for feeding by the high-spin isomer through the 697-keV cascade transition. Further justification for this procedure is given in the discussion of the decay scheme in Sec. III. The resulting modified decay curve for the 598-keV transition, which we postulate to represent the half-life of the low-spin isomer, is shown in Fig. 1. The half-life extracted using the above assumptions was 1.27 ± 0.30 s. The half-life of 0.57 ± 0.06 s for the "high-spin" isomer, is in good agreement with the value of 0.61 ± 0.10 s obtained from delayed-neutron measurements,[3] but disagrees with the value of 0.35 ± 0.08 obtained by Lund *et al.*[2]

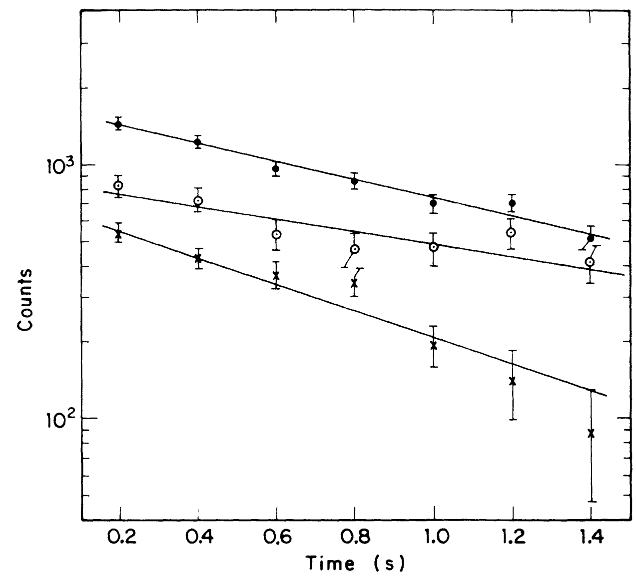

FIG. 1. Decay curves for the 598-keV γ ray (upper curve) and 697-keV γ ray (lower curve) following the decay of ^{76}Cu. The lines represent half-lives of 0.84 s and 0.57 s, respectively. The middle curve has been fit to a half-life of 1.27 s and represents the decay of the 598-keV γ ray after subtracting out the feeding from the 697-keV transition (see Sec. II C).

^{76}Cu is the most neutron-rich nucleus known with A=76 and thus provides a test of half-life predictions of the older gross theory of Takahashi, Yamada, and Kondoh[8] and the more recent work of Klapdor, Metzinger, and Oda[9] in which structures of the β strength function have been taken into account. The gross theory predicts for ^{76}Cu a half-life range of 1 to 3 s, while the newer theory predicts 0.244 s. Our results fall between these two extremes. A similar situation was found to exist for the ^{74}Cu half-life.[5]

D. γ-ray energies, intensities, and coincidence relationships

A typical β-gated γ singles spectrum taken at the point of deposit is shown in Fig. 2. The energy range shown is from 0.02 to 2.0 MeV. (The highest energy ^{76}Cu γ ray identified was at 1783 keV.) In Fig. 3 the γ-ray spectra in coincidence with the 598- and 1337-keV transitions are shown from 0 to 1.5 MeV.

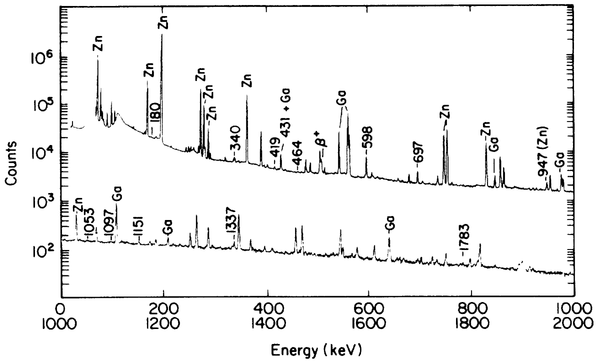

FIG. 2. γ-ray singles spectrum from the A=76 source with data collection cycle set to emphasize short half-lives. The γ rays from ^{76}Cu decay are indicated by their energies in keV. Strong γ rays from ^{76}Zn and ^{76}Ga decay are labeled by Zn and Ga, respectively. The peak at 947 keV is interpreted to be a sum peak from ^{76}Zn decay.

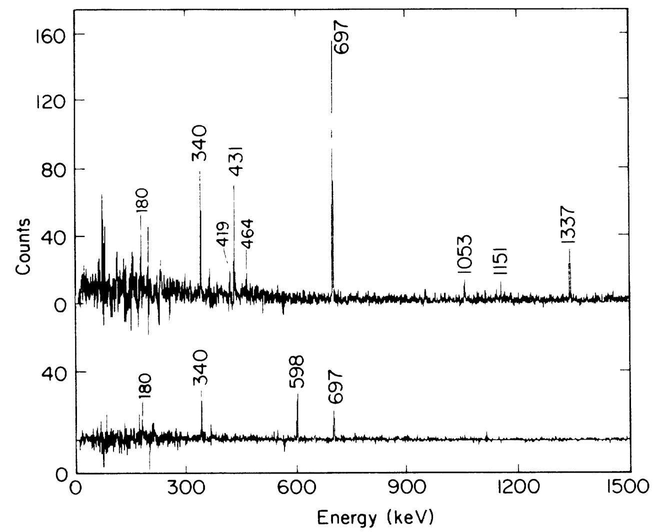

FIG. 3. γ-ray spectra in coincidence with the 598-keV (upper curve) and 1337-keV (lower curve) γ rays, respectively. The Compton background has been subtracted.

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 carried out. We emphasize that the relative γ-ray intensities presented here are dependent on the relative populations of the two isomers from our ion source and thus could differ under other experimental conditions. They are based on the long main run described in Sec. II B.

Prior to this work, Lund et al.[2] reported three γ rays from ^{76}Cu decay at 598, 697, and 947 keV but no relative intensities were given. The energies for the first two correspond to the two strongest γ rays observed in this work at 598.68 and 697.78 keV. We also observed a peak at 947 keV but interpret it as a sum peak from the 199.2- and 748.72-keV γ-ray cascade in ^{76}Zn decay.[10]

TABLE I. γ transitions observed in ^{76}Cu decay.

E_γ (keV)	I_γ^a	Placement (keV)	Coincident γ rays[b] (keV)
180.2(3)	3.2(11)	2813–2633	598,697,1337
340.89(7)	16.4(12)	2974–2633	(419)[d],(431)[d],598,697,(1151)[d],1337
419.50(7)	9.7(7)	1715–1296	(340)[d],(598),697
431.83(8)	9.5 (9)[c]	1030–598	(340)[d],598,1783
464.42(21)	2.9(7)	1760–1296	598,697,(1053)
598.68(5)	100.(3)	598–0	180,340,(419),431,(464),697, 1053,1151,1337
697.78(5)	52.9(20)	1296–598	340,419,464,598,(1053),1337
1053.4(5)[e]	2.4(10)[e]	2813–1760	(464),598,697
1097.6(5)	3.0(13)	2813–1715	
1151.3(5)	6.(3)	unplaced	598
1337.08(8)	30.2(20)	2633–1296	(180),340,598,697
1783.46(21)	7.0(11)	2813–1030	431,(598)

[a]Normalized to 100 for the intensity of the 598-keV γ ray. The relative intensities depend on the relative population of the two ^{76}Cu isomers in the source.
[b]Possible coincidences are indicated by parentheses.
[c]Intensity from 598-keV coincidence gate. Peak contaminated by 431-keV γ ray from ^{76}Ga decay.
[d]Weak (possible) coincidences linking the 340-keV γ ray with lower lying levels are observed, but due to poor statistics possible linking γ transitions were not observed.
[e]Energy and intensity obtained from various coincidence spectra.

III. THE ^{76}Cu DECAY SCHEME

The level scheme for ^{76}Zn populated in ^{76}Cu decay and shown in Fig. 4 is based on the γ-ray singles and coincidence measurements presented here. Of 12 γ rays ascribed to ^{76}Cu decay, 11 were placed in the ^{76}Zn level scheme. Analysis of the level scheme shows the largest level energy errors to be 0.21 and 0.17 keV for the 1760- and 2813-keV levels, respectively. All others have errors less than 0.13 keV, therefore we present the level energies to two significant figures beyond the decimal point. Due to the predominance of higher Z members of the A=76 decay chain, we are very conservative in ascribing γ rays to ^{76}Cu decay. The levels observed are discussed below.

A. ^{76}Cu Isomers

We postulate two long-lived ^{76}Cu isomers based on the coincidence between the strong 598- and 697-keV γ rays, the fact that their half-lives are definitely different (see Fig. 1), and also that neither of these γ rays has been observed from longer-lived members[4,10] of the A=76 decay chain. Isomerism is not observed for low-mass ($A < 68$) even-A Cu nuclides in which the protons and neutrons are filling the same $(1f_{5/2}, 2p_{3/2})$ subshell. For A=68 and above, the neutrons fill the $(2p_{1/2}, 1g_{9/2})$ subshells and isomerism has been observed[11,12] for ^{68}Cu and ^{70}Cu. In each case the ground state is 1^+ (presumably from $\pi 2p_{3/2} \otimes \nu 2p_{1/2}$), and the excited isomer has $J \geq 4$ (presumably from $\pi 2p_{3/2} \otimes \nu 1g_{9/2}$ or $\pi 1f_{5/2} \otimes \nu 1g_{9/2}$). Although isomerism has not been observed[5,13] for ^{72}Cu and ^{74}Cu, the same configurations producing isomerism in ^{68,70}Cu could also produce both high- and low-spin isomers in ^{76}Cu. In β^- decay, the low-spin isomer in ^{68,70}Cu populates only states with $J \leq 2$, whereas the high-spin isomer populates by β^- decay only states with $J \geq 4$. A similar situation thus appears reasonable for ^{76}Cu decay, however, J=3 seems possible. No γ transitions connecting the ^{76}Cu isomers were observed.

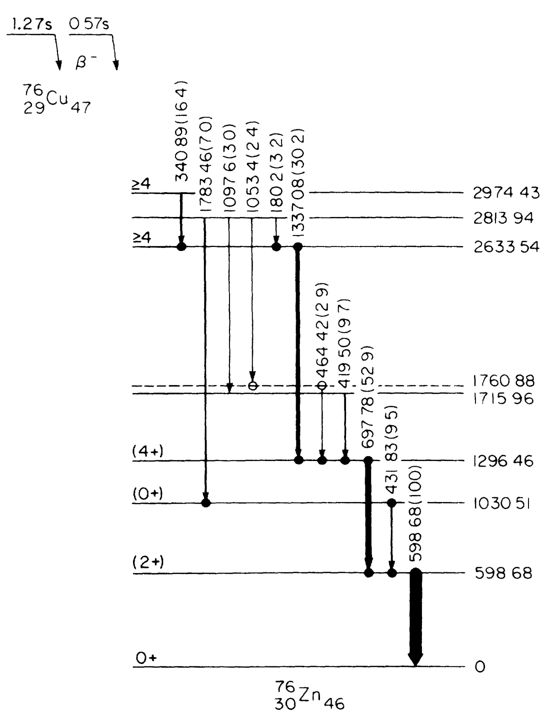

FIG. 4. Decay scheme for ^{76}Cu with energies in keV. The 0.57 s half-life is probably from the decay of a high-spin isomer while the 1.27 s half-life is probably from the decay of a low-spin isomer.

B. Levels in ^{76}Zn below 1.5 MeV

We present here our proposed level scheme for ^{76}Zn. The first-excited state at 598 keV is postulated to be 2^+ based on systematics and the fact that the 598-keV γ ray is the strongest observed. The level is also well established by numerous coincidences. A striking feature of the ^{76}Cu decay scheme is a cascade of the four strongest γ rays of energy 340, 1337, 697, and 598 keV with respectively larger intensities. The above γ rays are in mutual coincidence. This feature has also been observed[11,12] in the decay of the high-spin isomer of ^{68,70}Cu, and in each case the state above the 2_1^+ state in the cascade is postulated to be 4_1^+. We thus postulate a level at 1296 keV and tentatively give it a model-dependent assignment of $J^\pi = 4^+$.

A γ ray at 431 keV is in strong coincidence with the 598-keV transition but no other members of the "high-spin" cascade. We thus postulate a level at 1030 keV. From systematics this level is likely to be 0_2^+ or 2_2^+. No transition to the ground state was observed, thus we tentatively give the 1030-keV level a model-dependent assignment of $J^\pi = 0^+$. It is conceivable, considering the errors of the intensity of the 431- and 1783-keV γ rays, that the order of the above two transitions is reversed placing the "1030-keV level" at 2382 keV. From systematics a 2_2^+ level is expected that would populate both the ground state and the 2_1^+ level. We do not have a good candidate for the 2_2^+ level.

C. Levels in ^{76}Zn above 1.5 MeV

A pair of levels are postulated at 1715 and 1760 keV. Cascades from the 2813-keV level pass through the above two levels on their way to the 1296-keV level. The depopulating γ rays from the pair are in coincidence with both the 697- and 598-keV γ rays. The order of the cascading γ rays from the 2813-keV level is determined solely by relative intensities. For the 1053–464-keV cascade, the order could certainly be inverted due to uncertainties in the intensities and a lack of γ rays observed to feed or depopulate the intermediate level. This would give a level at 2349 keV. The 1760-keV level is thus dashed in Fig. 4 to reflect this uncertainty.

A triplet of levels was inferred at 2633, 2813, and 2974 keV. Roughly half of the β^- feeding in this experiment populates these three states. This situation is similar to that observed for ^{74}Zn in which a group of five levels between 2.5 and 3.0 MeV receive almost half of the β^- feeding.[5] The 2813-keV level is depopulated by four γ rays and confirmed by a number of coincidences. Its decay pattern is rather strange in that it apparently deexcites to both a 0^+ and 4^+ level. This difficulty could be resolved by postulating a closely spaced doublet in which the low-spin member populates the 0_2^+ level. The present data are not of high enough quality to justify such an assumption and further experiments are needed to clarify this point. The 2633- and 2974-keV levels are involved in the "high-spin" cascade. Based on systematics for even-A Cu isomer decay and the absence of transitions to low-spin levels, we would expect the 2633- and 2976-keV levels to have $J \geq 4$. From shell-model arguments these levels would be fed by a negative parity state in ^{76}Cu. The β transition would thus be allowed if these ^{76}Zn levels had negative parity.

An alternative placement for the 340-keV transition would be populating the level at 2813 keV. Such a placement would account for some weak coincidence information (see Table I, footnote d), but we do not observe coincidences between the 340- and 180-keV γ rays so we choose instead to place the 340-keV γ ray populating the 2633-keV level.

IV. SYSTEMATICS AND SHELL-MODEL CALCULATIONS FOR EVEN-*A* NEUTRON-RICH Zn NUCLEI

In Fig. 5 the known energy systematics from 0 to 3 MeV for even-A Zn isotopes are shown. The systematics

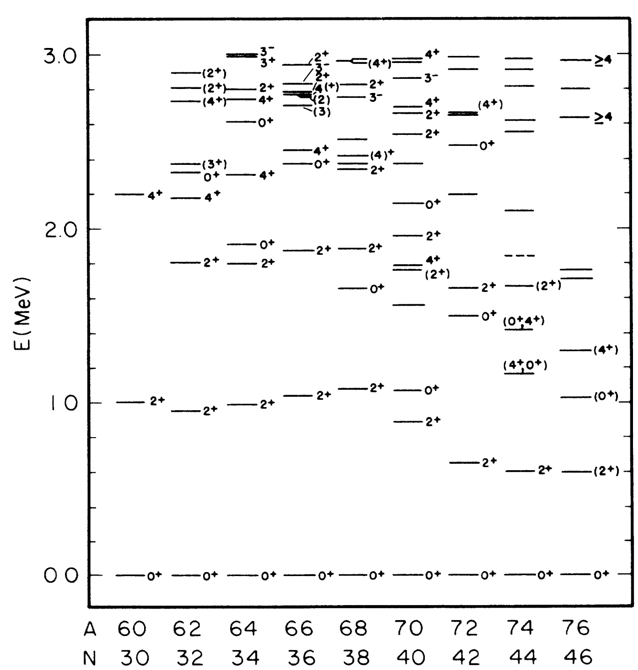

FIG. 5. Systematics for even-A Zn isotopes from A=60 to 76.

of the 2_1^+ states are especially interesting. The 2_1^+ energy is essentially constant at around 1 MeV from N=30 to 38 which corresponds in the simple shell-model picture to the filling of the neutron $1f_{5/2}$ and $2p_{3/2}$ subshells. An interesting parallel is observed for the Fe isotopes (two proton holes) with N=30 to 36 where the energy of the 2_1^+ state is roughly constant at about 0.85 MeV. A striking feature of the Zn systematics is that the energy of the 2_1^+ state drops from 1077 keV at ^{68}Zn, where the $(1f_{5/2},2p_{3/2})$ neutron subshell is filled, to 598 keV at ^{76}Zn as the $(2p_{1/2},1g_{9/2})$ neutron subshells are filling. The 0_2^+ and 4_1^+ states appear to follow a similar pattern. These trends are discussed in more detail below. Calculations for even-A Zn nuclei have been extended to ^{76}Zn. Since the procedure was the same as that used earlier[5] for ^{74}Zn, we will not describe the calculation in detail but will briefly outline the major points. The calculation was performed with the code OXBASH.[14] The proton model space was taken to be $1f_{5/2},2p_{3/2},2p_{1/2},1g_{9/2}$ and the neutron space was taken to be $2p_{1/2},1g_{9/2}$ which corresponds to a closed core of $^{66}_{28}$Ni$_{38}$. The assumption that N=38 is a good closed subshell is certainly not a good assumption near A=66 but it is assumed here that as N increases above 38 the orbitals below 38 fall rapidly below the Fermi surface and soon become of minor importance.

For the protons, the Ji-Wildenthal interaction[15] 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) which 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 $A \approx 66$ 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.

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.*,[16] then the pn and nn TBME involving the $(2p_{1/2},1g_{9/2})$ subshells were replaced by a modification by Brown[17] of the "seniority-fit total-energy" TBME of Serduke, Lawson, and Gloeckner.[18] As was the case with the protons, it was found that the neutron SPE appropriate for the $A \approx 90$ region (where this neutron interaction was designed to work) are not suitable for the $A \approx 66$ region. Consequently, the two values of neutron SPE were chosen to fit the binding energies of the first $1/2^-$ and $9/2^+$ states of ^{69}Zn, and then assumed to vary linearly with proton number for Z=28 to 40 (where they were previously determined for the A=90 region). A listing of the SPE and TBME is available from one of the authors (E.K.W.).

In Fig. 6, the calculated 0^+, 2^+, and 4^+ states for

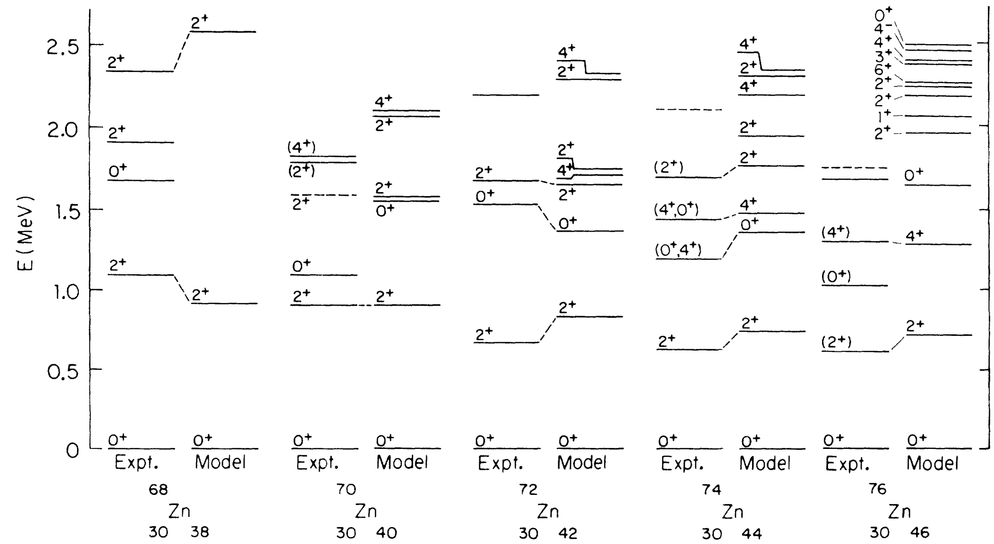

FIG. 6. Comparison of predicted and experimental 0^+, 2^+, and 4^+ levels of $^{68-76}$Zn. All predicted $0^+, 2^+, 4^+$ levels below 2.4-MeV excitation are shown. For ^{76}Zn all levels below 2.5-MeV excitation are shown.

$^{68-76}$Zn are compared to experiment. "For ^{76}Zn we indicated all levels up to 2.5 MeV." It is worth noting that the model indicates the 8_1^+ level to be at 3.163 MeV and only two negative parity states between 2.5 and 3.0 MeV, namely the 5_1^- at 2.705 MeV and the 3_1^- at 2.889 MeV. The model gives 17 positive parity states between 2.0 and 3.0 MeV. Reasonable agreement is observed for the above states up to about 2 MeV. The major occupancy of the calculated wave functions for the 0_1^+, 2_1^+, 0_2^+, 2_2^+, and 4_1^+ states are $1f_{5/2}$ and $2p_{3/2}$ for the protons and $2p_{1/2}$ and $1g_{9/2}$ for the neutrons (due to the restricted model space for neutrons).

An important feature of the systematics shown in Fig. 6 is that the 2_1^+ states drop a factor of two in energy from ^{68}Zn to ^{76}Zn. Similar decreases in energy are also noted for the 0_2^+ and 4_1^+ states. These features are also somewhat evident in the calculated levels, but the energy decrease is less dramatic than for the experimentally determined levels.

A first attempt was made to extend the shell-model calculations to all even-A Zn nuclei from ^{60}Zn to ^{76}Zn. For these calculations, the shell-model space includes all neutron orbitals for N between 28 and 50 and the proton orbitals for Z between 28 and 40. In these calculations, ^{56}Ni is taken to be a doubly magic core about which both neutrons and protons are coupled. In the initial calculations, an SDI interaction was used to determine the TBME while the SPE came from analysis of nearby odd-A nuclei. The basic goal of these calculations is an attempt to reproduce over the entire model space the striking behavior of the 2_1^+, 0_2^+, and 4_1^+ energies seen in systematics. Neither a simple linear variation of SPE between the appropriate values at the extremes of the model space nor a simple scaling of TBME have been found to be satisfactory.

V. CONCLUSIONS

In this paper the postulation of excited states in ^{76}Zn is presented. 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 $1g_{9/2}$ orbitals. Reasonable agreement is obtained between experiment and the calculation for states below 2.0 MeV in excitation energy. The dominant proton components for states below 2.3 MeV in ^{76}Zn are almost entirely $1f_{5/2}$ and $2p_{3/2}$. Calculations involving the full shell between the magic numbers 28 and 50 using a SDI do not reproduce the observed systematics in Zn nuclei indicating the need for a more realistic interaction.

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