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High-spin states in ^{68}Zn

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Yrast levels of ^{68}Zn have been investigated via measurements of excitation functions and angular distributions of single γ rays and of γ-γ coincidences following the ^{65}Cu($\alpha, p\,\gamma$)^{68}Zn reaction with α particle energies between 12–21 MeV. Spins up to $8\hbar$ were assigned to observed states.

[NUCLEAR REACTIONS ^{65}Cu($\alpha, p\gamma$), $E_\alpha = 12$–21 MeV; measured γ, γ-γ, $\sigma(E_\gamma, \theta_\gamma)$, deduced ^{68}Zn decay scheme, J, π, and γ mixing. Enriched target, Ge(Li) detectors.]

I. INTRODUCTION

The work is a part of a systematic study of high-spin levels in the even-even isotopes nuclei of zinc by in-beam γ-ray spectroscopy using nuclear compound reactions.[1,2] It is especially difficult to reach the ^{68}Zn residual nucleus with a cross section convenient with respect to those of the others outgoing channels in a fusion-evaporation reaction, because of the relative neutron excess of this nucleus. Thus it is unreasonable to try to obtain ^{68}Zn via the ^{66}Zn($\alpha, 2p\gamma$) reaction: we have verified in the energy range $E_\alpha = 25$–33 MeV that only three compound reactions may be observed, corresponding to the ($\alpha, pn\gamma$), ($\alpha, 2n\gamma$), and ($\alpha, \alpha n\gamma$) outgoing channels. So we have used a reaction in which essentially one particle is evaporated, which makes it easier to observe when the cross section is weak. During bombardment of an enriched ^{65}Cu foil with 18 MeV α particles we have observed the γ rays emitted in the ^{65}Cu($\alpha, n\,\gamma$)^{68}Ga and ^{65}Cu($\alpha, p\gamma$)^{68}Zn reactions, the first one being 17 times more intense than the second. This is particularly inconvenient because of the decay of ^{68}Ga nucleus ($T_{1/2} = 68$ min) feeding the 1077 keV level in ^{68}Zn with a percent branching of 3.2% (Ref. 3). A small contribution of the ($\alpha, 2n\gamma$) channel has also been observed at $E_\alpha = 18$ MeV, but a convenient yield of the high-spin levels in ^{68}Zn requires this E_α value.

It will be noted that the ^{65}Cu($\alpha, p\gamma$)^{68}Zn reaction at $E_\alpha = 18$ MeV does not allow one to reach very high-spin states because the incident α particles induce in the compound nucleus an angular momentum whose extreme value is nearly $10\hbar$, while the evaporated proton removes one or two $\hbar$. If we suppose that the same high-spin states may be uncovered in nuclei of the (f, p) shell by ($\alpha, 2n\gamma$) reactions at $E_\alpha = 30$ MeV or (HI, xn, yp, $z\alpha\gamma$) reactions,[1] it would seem reasonable that the ^{65}Cu($\alpha, p\gamma$) reaction at $E_\alpha = 18$ MeV would not be an economical way to investigate all the high-spin levels in ^{68}Zn. Then the ^{48}Ca(^{22}Ne, $2n\gamma$)^{68}Zn reaction would be a better reaction and we hope to do this experiment in the future on the Grenoble cyclotron if an intense enough ^{22}Ne beam of 25 MeV can be extracted.

The nucleus ^{68}Zn has been previously studied through several different nuclear reactions: ^{68}Zn(p, p') (Refs. 4–6), ^{68}Zn(d, d') (Refs. 7, 8), ^{68}Zn(α, α') (Refs. 9–12), ^{66}Zn(t, p) (Refs. 5, 13), ^{67}Zn(n, γ) (Refs. 14, 15), ^{64}Ni(^{6}Li$, d$) (Ref. 16), ^{64}Ni(^{16}O, ^{12}C) (Ref. 17) and through the decay of ^{68}Ga (Refs. 3, 18, 19) and ^{68}Cu (Refs. 20, 21). Some ambiguities in spin-parity assignment of high-spin levels previously observed through the decay of the $J^\pi = 6^-$ isomeric state of ^{68}Cu (Ref. 21) have been solved in the present study, and spins up to $8\hbar$ were assigned to new levels.

II. EXPERIMENT AND RESULTS

The present study of the ^{65}Cu($\alpha, p\gamma$)^{68}Zn reaction has been performed with the experimental setup used at the Grenoble cyclotron, except for some points of yield functions, which have been measured using the tandem Van de Graaff of the CEN Saclay. Six types of measurements were performed using an enriched (99%) self-supporting ^{65}Cu target (5 mg/cm^2) and large volume Ge(Li) detectors (50–80 cm^3) with a typical resolution of 3 keV at 1.33 MeV:

γ-ray energy measurements. The γ-ray energies were measured by taking singles spectra at 90° to the beam direction. The adopted transition energies listed in Table I are averages of the values measured at $E_\alpha = 18$ MeV and $E_\alpha = 21$ MeV.

Relative γ-ray excitation functions. Excitation functions were determined for six bombardment energies in the energy range 12 to 21 MeV and measured from singles γ-ray spectra taken at 55° to the beam. Figure 1 shows the γ-ray intensities normalized to the 1340 keV ($4^+ \to 2_1^+$) transition which is common to all cascades (the 1077 keV γ -ray corresponding to the $2_1^+ \to 0^+$ ground-state (g.s.) transition is contaminated by the radioactive decay of ^{68}Ga nuclei). The slope of

TABLE I. γ ray energies and intensities in the ^{65}Cu(α,p)^{68}Zn reaction at $E_\alpha = 18$ MeV.

Energy J^π Initial state	 Final state	E_γ [a] (± 0.5 keV)	Relative intensity [b] ($\pm 10\%$)
1077.3 2^+	g.s. 0^+	1077.3	100
1883.1 2^+	1077.3 2^+	805.8	10
1883.1 2^+	g.s. 0^+	1883.5	16
2417.5 4^+	1077.3 2^+	1340.2	80
3458.1 5^-	2417.5 4^+	1040.6	47
3687.6 6^+	2417.5 4^+	1270.1	23
3610.1 6^-	3458.1 5^-	152.0	23
3942.2 (8^-)	3610.1 6^-	332.1	10 [c]
4396.9 8^+	3687.6 6^+	709.3	17

[a] Average values of γ-ray energies observed at $E_\alpha = 18$ and 21 MeV, fitted using a quadratic energy calibration.

[b] Measured at 55° to the beam axis. The 1077 keV γ-ray intensity was corrected for the radioactive decay of ^{68}Ga.

[c] Doublet: the 332 keV γ ray is contaminated with a weak 334 keV γ ray.

the excitation functions gives an indication of the spin of the level from which the γ rays originate, being larger for higher-spin states. The relative γ-ray intensities measured at $E_\alpha = 18$ MeV and at 55° to the beam axis are listed in Table I.

γ-γ coincidences. We performed prompt and delayed γ-γ coincidences at $E_\alpha = 18$ MeV. The two Ge(Li) detectors were used in the horizontal plane at 90° and 55°, respectively, to the beam axis. The γ-γ coincidences were stored on a magnetic tape connected to a PDP-9 computer and the size of the matrix was 1024×2048 channels.

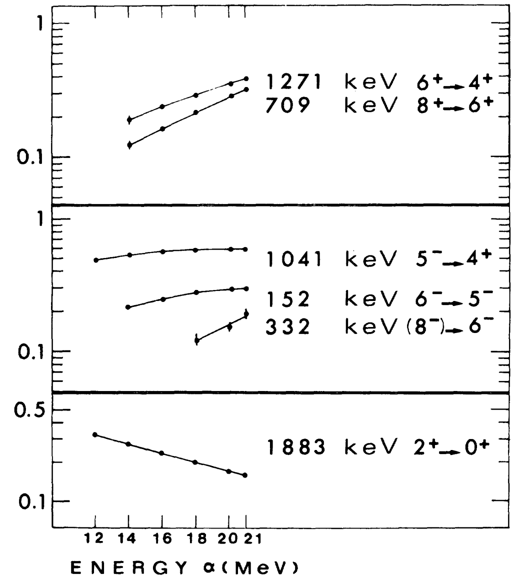

FIG. 1. Excitation function of the γ rays emitted between ^{68}Zn levels populated in the ^{65}Cu(α,$p\gamma$)^{68}Zn reaction. Intensities are normalized to the 1340 keV transition (the 1077 keV γ ray has an intensity perturbed by the radioactive decay of ^{68}Ga). Some γ rays are not seen when the α particle energy is lower than 14 MeV.

The time window was about 10 ns wide for the prompt γ-γ coincidences. For the delayed γ-γ coincidences, the time window was chosen so that the delay between two γ-rays was in the range 20–50 ns (the time interval between beam bursts was 92 ns at $E_\alpha = 18$ MeV). Prompt γ-γ coincidence spectra are shown in Fig. 2. It will be noted that a weak 334 keV transition (not placed) appears in coincidence with the 332 keV γ ray. Delayed γ-γ coincidences revealed only that the 152 keV transition is slightly delayed with respect to the 332 keV γ ray. Figure 3 shows the level scheme deduced from γ-γ coincidences and single γ-ray intensity measurements.

Angular distributions. Measurements were performed at $E_\alpha = 18$ MeV with two Ge(Li) detectors. One was placed at 90° to the beam axis and used as a monitor, the other one was mounted so that it could rotate round the target at 25 cm from it and spectra were recorded at seven angles from 90° to 30° with respect to the beam line. The solid angle correction factor coefficient Q_K[22] were neglected and no Doppler effect was observed at forward angles (the target thickness was 5 mg/cm^2). The analysis of the data was performed using the formula and notation of Yamazaki[23] with the assumption that the distribution of the m substate population is Gaussian. The results are summarized in Table II. The angular distribution of the 1077 keV γ ray ($2_1^+ \rightarrow 0^+$ g.s. transition) is perturbed by radioactive decay of ^{68}Ga, and no significant fit parameters may be deduced from the data analysis. The well known $2_2^+ \rightarrow 2_1^+$ (806 keV) and $2_2^+ \rightarrow 0^+$ g.s. (1883 keV) transitions were not analyzed because of poor statistics. The angular distribution of the 332 keV γ ray (located at the Compton edge of the 511 keV annihilation and contaminated with a weak 334 keV

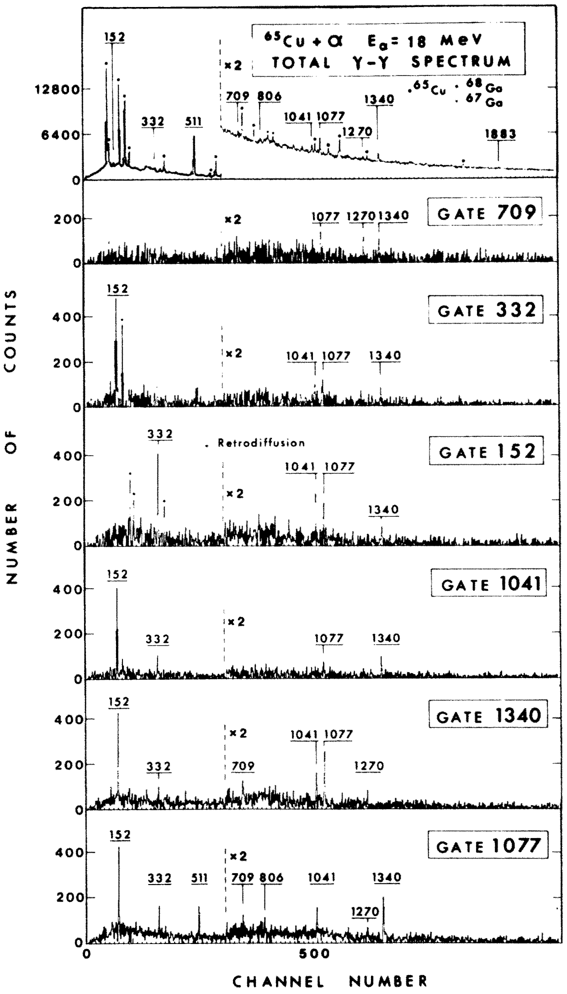

FIG. 2. Prompt γ-γ coincidences spectra. Upper part: Total γ-γ coincidences spectrum. The most intense γ rays associated with the various outgoing channels are indicated. Lower parts: Selected spectra observed in coincidence with events in the indicated gate regions, and with subtracted background. The γ-ray energies are in keV, and precise values are given in Table I.

γ ray) was obtained with such statistical errors that we cannot have complete confidence in the fit parameter analysis, and the $L = 2$ characterization must be retained only with caution.

It will be noted that the general trend toward disorientation is consistent with theoretical predictions: as one would expect, the α_2 values (spin alignment parameters) decrease going down a cascade because each successive γ ray causes further disorientation of the nucleus. In particular, the $\alpha_2(J_i)$ value deduced from the angular distribution analysis of the 1340 keV γ ray deexciting the 2417 keV level is found nearly equal to the intensity-weighted average of the $\alpha_2(J_f)$ values associated with the 1041 and 1270 keV γ rays feeding this level (the side feeding is weak).

DCO ratio measurements

From the γ-γ coincidence measurements performed with two Ge(Li) detectors respectively at 90° and 55° to the beam direction, we may deduce directional correlation from oriented states (DCO) ratios. The DCO method of analysis has been described in detail by Krane, Steffen, and Wheeler[24] and employed successfully[25,26]: this method uses the coincidence rates $W(A(\gamma_1), B(\gamma_2))$ and $W(A(\gamma_2), B(\gamma_1))$ of two γ rays γ_1 and γ_2 that are emitted from an oriented ensemble of nuclei and are observed by two detectors A and B fixed at asymmetric directions with respect to the beam axis. The ratio $R(A,B) = W(A(\gamma_1), B(\gamma_2))/W(A(\gamma_2), B(\gamma_1))$ of the two coincidence rates is a very practical observable for the determination of multipole-mixing ratios of γ transitions and spin sequences.

In heavy-ion-induced fusion-evaporation reactions the Ge(Li) detectors can be placed at $\theta_A = 90°$ and $\theta_B = 0°$ to the beam axis in the horizontal plane in order to increase the sensitiveness of the method, but in an α-induced reaction the beam is stopped in a Faraday cup far from the target and it is not possible to place a Ge(Li) detector at 0°.

Experimental restraints (a geometrical detector arrangement for a convenient rate of γ-γ coincidences) allow us to place Ge(Li) at $\theta_A = 90°$ and $\theta_B = 55°$, but with these θ values the DCO method requires an accurate measurement of the

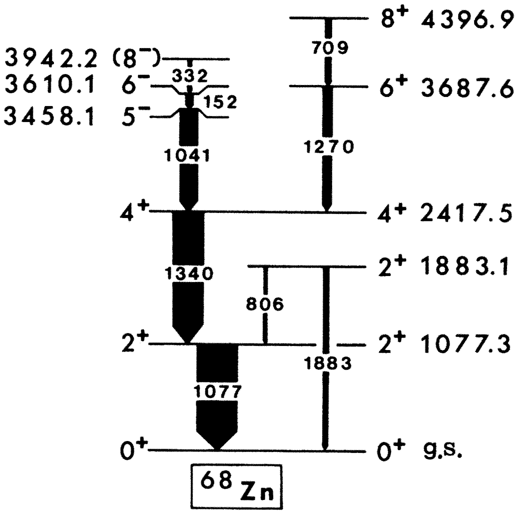

FIG. 3. Decay scheme of ^{68}Zn. Assignment of J^π values are based on angular distribution analysis, yield functions, electronic timing measurements, no cross-over transition observations within a 5% intensity limit, and DCO ratio measurements; for the degree of confidence see the text.

TABLE II. Results of the angular distribution measurements in ^{68}Zn.

E_γ	Transition	Angular distribution coefficients [a] $A_2 \pm \Delta A_2$	$A_4 \pm \Delta A_4$	σ_i	$\alpha_2(J_i, \sigma_i)$	$\alpha_2(J_f, \sigma_i)$	$\delta \pm \Delta\delta$	Multipolarity
1077.3	$2^+ \rightarrow 0^+$	0.12 ±0.10	−0.21 ±0.18	1.6	c	c	0	$E2$
1340.2	$4^+ \rightarrow 2^+$	0.24 ±0.03	−0.01 ±0.05	2.2	0.44	0.31	$0.02^{-0.02}_{+0.05}$	$E2$
1270.1	$6^+ \rightarrow 4^+$	0.41 ±0.05	0.0 ±0.05	2.2	0.65	0.58	$0.14^{-0.04}_{+0.05}$	$E2$
709.3	$8^+ \rightarrow 6^+$	0.35 ±0.05	−0.11 ±0.06	2.4	0.77	0.72	$0.05^{-0.08}_{+0.02}$	$E2$
1040.6	$5^- \rightarrow 4^+$	−0.06 ±0.03	0.10 ±0.10	2.7	0.44	0.40	$0.07^{-0.05}_{+0.05}$	$E1$
152.0	$6^- \rightarrow 5^-$	−0.20 ±0.03	−0.01 ±0.05	2.9	0.48	0.46	$-0.05^{-0.06}_{+0.08}$	$M1$
332.1	$(8^-) \rightarrow 6^-$	0.125 ±0.10	0 ±0.18	c	c	c	c	$L=2$

[a] $W(\theta) = 1 + A_2P_2(\cos\theta) + A_4P_4(\cos\theta)$.

[b] Calculation performed using formula and notations of Yamazaki (Ref. 23). The alignment parameter α_2 is computed using a Gaussian substate population distribution of width σ.

[c] See the text: No significant fit parameter may be deduced from data analysis.

coincidence ratio. Unfortunately, the relative weakness of the ^{65}Cu($\alpha, p\gamma$)^{68}Zn reaction cross section give us a large statistical dispersion (see Fig. 2 and Table III), so we have used the DCO ratio essentially to verify the consistency with the angular distribution analysis. Calculations were performed with the computer code CORAM[27] and results are given in Table III. It will be noted that a $L=2$ characteristic for the 332 keV transition is suggested.

Electronic timing measurements

Using the pulsed beam from the cyclotron at $E_\alpha = 18$ MeV we have looked at the γ rays delayed with respect to the high frequency signal in a 60 ns time range. Two delayed γ rays in ^{68}Zn were observed, the 152 and 332 keV transitions, for which we can give only the maximum values $T_{1/2}$(152 keV) < 2.5 ns and $T_{1/2}$(332 keV) < 6 ns because of the time resolution of the experimental setup and of the relatively weak statistics.

TABLE III. Experimental and theoretical DCO ratios $R(90°, 55°)$ for the γ-γ cascades in ^{68}Zn following the ^{65}Cu($\alpha, p\gamma$)^{68}Zn reaction.

γ_1 (keV)	γ_2 (keV)	$R(90°, 55°)$ Expt. ±0.2	$R(90°, 55°)$ Theor. [a]	Assumed transition
1340	1077	1.04	0.97	$4^+ \rightarrow 2^+ \rightarrow 0^+$
1270	1340	1.12	0.95	$6^+ \rightarrow 4^+ \rightarrow 2^+$
709	1270	1.05	1.04	$8^+ \rightarrow 6^+ \rightarrow 4^+$
1041	1340	1.36	1.20	$5^- \rightarrow 4^+ \rightarrow 2^+$
152	1041	1.19	1.02	$6^- \rightarrow 5^- \rightarrow 4^+$
332	152	0.80	0.75	$8^- \rightarrow 6^- \rightarrow 5^-$

[a] Calculations performed using σ and δ values deduced from angular distributions analysis except for the 332 keV γ ray, for which $\sigma = 3.0$ and $\delta = 0.0$ were assumed.

III. PROPOSED DECAY SCHEME AND ASSIGNMENT OF J^π VALUES

Assignments of J^π values are based on angular distribution analysis, yield functions, electronic timing measurements, no crossover transition observations, and DCO ratio measurements. Referring to Figs. 2 and 3 and Tables I, II, and III, we now discuss spin and parity assignments. The 2^+ states at 1077 and 1883 keV are well known.[28] We confirm the assignment 4^+ (Ref. 15) for the 2417 keV state.

The 3458 keV level has been observed in the ^{68}Cu^m decay[21] as a possible $J^\pi = 5^-$ or 6^- state, in the ^{66}Zn(t, p) reaction[13] as a $J^\pi = 5^-$ state (at $E_x = 3451 \pm 10$ keV), and very probably in the ^{68}Zn(α, α') reaction[12] as a $J^\pi = 5^-$ state (at $E_x = 3450 \pm 30$ keV). This level decays only to the 4^+ state at 2417 keV through a $L=1$ transition of 1041 keV that confirms the previous $J^\pi = 5^-$ assignment.

The 3610 keV level which has been observed in the ^{68}Cu^m decay[21] as a possible $J^\pi = 6^-$ or 7^- state is deexcited to the 5^- level at 3458 keV by a 152 keV γ ray the angular distribution analysis (and DCO ratio measurement) of which shows that it is a pure $L=1$ transition. The absence of transitions to the 2^+ and 4^+ states and the yield function of the 152 keV γ ray favor a spin $J=6$ for the level at 3610 keV. We propose a negative parity for this level because of the absence of transition to the 4^+ level at 2417 keV. The maximum half-life value ($T_{1/2} < 2.5$ ns) of the 152 keV γ ray does not exclude the $M1$ characteristic for this line.

The 3942 keV level, weakly excited in this experiment, decays to the 6^- level at 3610 keV by a 332 keV γ ray the angular distribution analysis and DCO ratio measurement of which suggest

TABLE IV. Comparison of levels energies and γ transition in ^{68}Zn and ^{70}Ge (Ref. 32) nuclei.

^{68}Zn by ^{65}Cu$(\alpha,p\gamma)$				^{70}Ge by ^{68}Zn$(\alpha,2n\gamma)$			
Initial level	→	Final level		Initial level	→	Final level	
J^π	E_x (keV)	J^π	E_x (keV)	J^π	E_x (keV)	J^π	E_x (keV)
2^+	1077	0^+	g.s.	2^+	1039	0^+	g.s.
2^+	1883	2^+	1037	2^+	1708	2^+	1039
2^+	1883	0^+	g.s.	2^+	1708	0^+	g.s.
4^+	2417	2^+	1077	4^+	2153	2^+	1039
6^+	3688	4^+	2417	6^+	3297	4^+	2153
8^+	4397	6^+	3688	8^+	4204	6^+	3297
5^-	3458	4^+	2417	5^-	3417	4^+	2153
6^-	3610	5^-	3458	6^-	3667	5^-	3417

a $L = 2$ transition. The yield function behavior of the 332 keV γ ray favors a spin $J = 8$ for the 3942 keV level. Taking into account the fact that the 332 keV γ ray is not so delayed as to be a $M2$ transition, we suggest a $J^\pi = (8^-)$ assignment for this new state in ^{68}Zn.

The 3687 keV state is deexcited to the 4^+ level at 2417 keV by a 1270 keV γ ray (pure $L = 2$). The slope of the yield function of this γ ray indicates a spin $J = 6$ for the 3687 keV level, and the absence of transitions from this level to the 5^- and 6^- levels above mentioned strongly suggests a positive parity. Furthermore, if the 1270 keV γ ray were a $M2$ transition, a Weisskopf estimation shows that this line would very probably have been observed as a delayed one (it is well established[29-31] that a $M2$ transition cannot be accelerated). Thus we assign $J^\pi = 6^+$ to the 3687 keV state.

The 4397 keV level decays only to the 6^+ level at 3687 keV by a 709 keV γ ray (pure $L = 2$). The behavior of the yield function, the absence of transitions to the 2^+, 4^+, 5^-, and 6^- levels, and the fact that this 709 keV γ ray was not observed as a delayed one, allow us to assign $J^\pi = 8^+$ to the 4397 keV state.

The 2753 keV level ($J^\pi = 3^-$) is very weakly excited in this experiment, which confirms that the compound (α, p) reaction produces preferentially yrast cascades.

IV. DISCUSSION

A complete shell model calculation of the ^{68}Zn nucleus is not possible at this time because of the large number of particles outside the closed shell. However, the great similarity between the level schemes of ^{68}Zn and ^{70}Ge(Ref. 32) will be noted [as we previously pointed out for ^{66}Zn and ^{68}Ge(Ref. 1)] (see Table IV), supporting the idea that the observed levels might be understood as neutron excited states. Thus we may speculate that positive-parity states (4^+, 6^+, 8^+) are associated with the $\nu[(1f_{5/2})^4{}_{0^+}(1g_{9/2})^2]^J$ configurations and negative-parity states (5^-, 6^-) are associated with the $\nu[(1f_{5/2})^4{}_{0^+}(1f_{5/2}1g_{9/2})]^J$ configurations.

This last suggestion has also been formulated by Swindle *et al.*[21] in their study of the decay of the ^{68}Cu isomers. Consequently, it is very reasonable to describe the 6^- isometric level in ^{68}Cu(^{68}Cu^m) as due to the coupling of a $2p_{3/2}$ proton to a $1g_{9/2}$ neutron according to Nordheim's weak

TABLE V. Positive-parity bands observed by means of γ spectroscopy in the even isotopes of zinc.

Isotope	Reaction	Reference	E_x (keV)	J^π	E_x (keV)	J^π	E_x (keV)	J^π
^{60}Zn	^{58}Ni(He$,n\gamma$)	34	1004	2^+	2193	(4^+)	···	···
^{62}Zn	^{60}Ni$(\alpha,2n\gamma)$	33	954	2^+	2186	4^+	3706	6^+
^{64}Zn	^{62}Ni$(\alpha,2n\gamma)$	2	991	2^+	2306	4^+	3993	6^+
^{66}Zn	^{64}Ni$(\alpha,2n\gamma)$	1	1039	2^+	2450	4^+	4179	6^+
^{68}Zn	^{65}Cu$(\alpha,p\gamma)$	This work	1077	2^+	2417	4^+	3688	6^+
^{70}Zn	^{70}Cu^b decay	35	885	2^+	1787	4^+	···	···

rule (this description was hypothesized by Singh *et al.*[20]), and to consider the β^- decay of the ^{68}Cu^m (allowed β^- transition) to be the transformation of a $1f_{5/2}$ neutron into a $2p_{3/2}$ proton.

Although these suggestions are appealing because of their simplicity, it would be interesting to confirm them by some theoretical calculations. In this way it is not unreasonable to think that a systematic knowledge of the high-spin levels in the pair isotopes of zinc would lead to the use of some approximations in a shell model calculation. In Table V we have summarized our results on ^{62,64,66,68}Zn with regard to 0^+, 2^+, 4^+, 6^+ yrast band and also the partial level schemes of ^{60}Zn (Ref. 34) and ^{70}Zn (Ref. 35), to take stock of the situation at the present time. It should be noted that the decrease of the excitation energies of the 4^+ and 6^+ states from ^{66}Zn to ^{70}Zn (assumed to be neutron states) is a consequence of the decrease of the energy gap between the $1g_{9/2}$ and $1f_{5/2}$ neutron shells.[36]

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