High-spin states in ^{66}Zn

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The structure of ^{66}Zn has been investigated by studying the yield functions, angular distributions, and coincidence relationships of the γ rays emitted during bombardment of an enriched ^{64}Ni foil by α particles of medium energy (27 MeV). Spins up to 10ħ were assigned to observed states.

[NUCLEAR REACTIONS ^{64}Ni(α, $2n\gamma$), E_α=22–40 MeV; measured γ, γ-γ, $\sigma(E_\gamma, \theta_\gamma)$, deduced decay scheme and J for high-spin states. Enriched target, Ge(Li) detectors.]

I. INTRODUCTION

The lowest $J^\pi = \frac{9}{2}^+$ states of ^{65,67}Zn have been observed as $L=4$ transfers in the (d,p) reaction on ^{64,66}Zn at excitation energies of 1.064 MeV and 0.602 MeV, respectively, and interpreted as single-particle states in which the transferred neutron occupies the $1g_{9/2}$ shell.[1] The neutron $1g_{9/2}$ shell is thus not far removed in energy from the $1f_{5/2}$ shell and consequently, among the states at a few MeV excitation in ^{66}Zn, one may expect those for which the neutron configurations lead to high spins.

The formation of such states necessitates the transfer of a large angular momentum which may be conveniently achieved by inducing compound nucleus reactions using heavy projectiles. We have verified in several cases that the same high-spin states may be formed in the f-p shell, using (α, $2n\gamma$) reactions or (HI, $xnypz\alpha$) reactions.[2,3] This is readily understandable since the notion of "high spin" in the f-p shell means $J \approx 10\hbar$, and the neutron evaporation removes less angular momentum than that of charged particles. Further, the large Doppler effect present in the heavy-ion reactions can provide a source of difficulty in measurements of γ-γ coincidences and γ-ray angular distributions, thus favoring the use of α projectiles when measurements based on Doppler effect are not required.

II. EXPERIMENTAL PROCEDURE

We have observed ^{66}Zn by several reactions: principally in the ^{64}Ni(α, $2n\gamma$) and ^{64}Zn(α, $2p\gamma$) reactions using α particles of 22–40 MeV; subsidiary measurements were also made using the reactions ^{63}Cu(α, $p\gamma$) at 22 MeV, ^{65}Cu(α, $p2n\gamma$) at 40 MeV, ^{68}Zn(α, $\alpha 2n\gamma$) at 40 MeV, and ^{56}Fe-(^{12}C, $2p\gamma$) at 40 MeV. The ^{64}Ni(α, $2n\gamma$) reaction at E_α = 27 MeV and 30 MeV was selected for the main study for the following reasons:

(1) At E_α = 27 MeV, the ^{64}Ni(α, $3n\gamma$)^{65}Zn reaction is completely eliminated and the only competing channel is the ^{64}Ni(α, $pn\gamma$)^{66}Cu reaction in which the disintegration of the radioactive final nucleus contributes little to ^{66}Zn. One must avoid significant formation of ^{66}Zn by radioactivity from other channels; thus the ^{64}Zn(α, $2p$)^{66}Zn reaction, for example, is unsuitable for the study of ^{66}Zn, since ^{66}Ga is mainly produced via the (α, pn) channel.
(2) Evaporation of neutrons was preferred to that of charged particles for the reasons outlined above. We performed γ-ray angular distributions at E_α = 30 MeV for a better yield of the high-spin levels.

Using beams from the Grenoble cyclotron, enriched (96.8%) self-supporting ^{64}Ni target (700 μg/cm^2), and large volume Ge(Li) detectors (50 – 100 cm^3) with a typical resolution of 3 keV at 1.33 MeV, five types of measurements were undertaken:

Direct γ spectra and γ-γ coincidences. The single γ spectrum and some gated spectra obtained using a 27 MeV α beam are shown in Fig. 1; the corresponding levels scheme is presented in Fig. 3. The main γ transitions are marked together with certain weak transitions whose existence is important for confirmation of assigned spin values.

Excitation functions. Figure 2 shows those of several transitions for α energies between 22 and 40 MeV, normalized to the 1039 keV ($2_1^+ \to 0_{g.s.}^+$) transition which is common to all cascades. The slope of the excitation functions gives an indication of the spin of the level from which the γ ray originated, being larger for higher-spin states.

Angular distributions. The results obtained using a 30 MeV α beam are presented in Table I. It will be noted that the given assignments result in a value of the spin-alignment parameter $\alpha_2(J)$ for each level, which remains nearly constant for all transitions to and from the level considered, the corresponding χ^2 being very close to its minimum value. We further note that, with our assignments, the parameters σ and the spin J of a given level are simply related through the relation $\sigma = aJ + b$, where a and b are positive constants (with one exception for the 627 keV transition).

Delayed γ rays. These could be observed in the 70 *ns* interval between beam bursts ($\nu_{HF} = 13.99$ MHz at $E_\alpha = 30$ MeV); lifetime measurements between 5 and 100 ns were thus possible. A problem is raised by the existence of a 1204 keV delayed

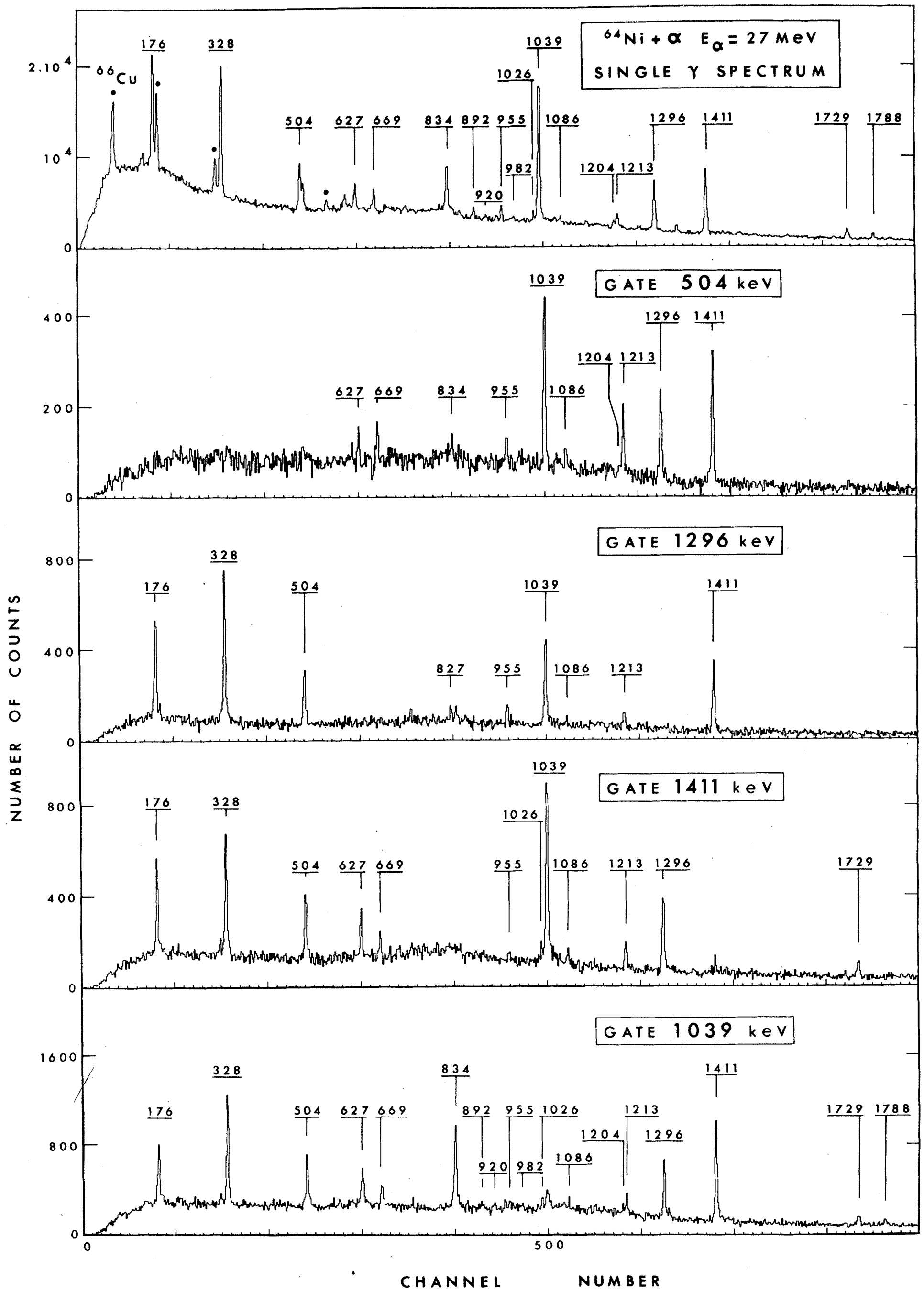

FIG. 1. Upper part: γ-ray spectrum following the bombardment of a ^{64}Ni target with 27 MeV α particles. Precise γ-ray energies are given in Table I. Lower parts: Selected spectra observed in coincidence with events in the indicated gate regions, and with subtracted background.

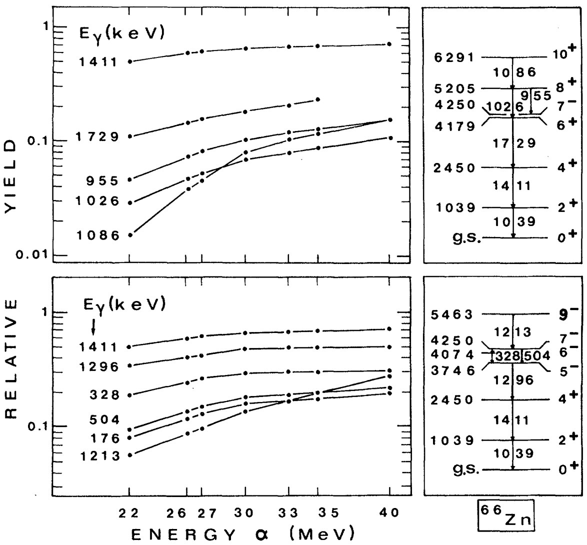

FIG. 2. Excitation functions of the γ rays emitted between ^{66}Zn levels populated in the ^{64}Ni($\alpha, 2n$)^{66}Zn reaction. Intensities are normalized to the 1039 keV transition. The 1729 keV γ ray is unresolved at $E_\alpha = 40$ MeV.

γ ray ($T_{1/2} = 17 \pm 2$ ns) which is apparently not the 1204 keV transition deexciting the 3077 keV level in ^{66}Zn (Fig. 3) since the associated 834 keV γ ray is not delayed; the origin of this transition may be found in the parasitic reaction ^{64}Ni($\alpha, \alpha n$)^{63}Ni. It will be noted that no other delayed transition has been observed in the 5 to 100 ns time range.

III. SYNTHESIS OF RESULTS

Referring to Figs. 2 and 3 and Tables I and II, we now discuss spin and parity assignments. The 2^+ states at 1039 keV and 1873 keV are well known. For the 2450 keV state, the assignment 4^+ (Refs. 5–7) is confirmed. The 2765 keV level has been observed in the ($p, p'\gamma$) reaction[8] by decay to the 2_1^+, 2_2^+, and 4_1^+ states and, with a very weak intensity, in the (γ, γ') reactions[9, 10] as a possible $J = (0, 1, 2)$ state. We exclude these values because of the presence of a 981 keV γ transition from the 5^- level at 3746 keV (subsequently assigned). A possible assignment consistent with the angular distribution analysis of the 892 keV transition which deexcites this level to the 2_2^+ level is $J = 3$; this state has not been observed in the (t, p) reaction,[11] thus it may be a $J^\pi = 3^+$ state. It will be noted that, with this assumption, the 981 keV γ ray is a $M2$ transition and its intensity seems to be rather too weighty compared to that of the 920 keV transition ($5^- \to 3^-$) when we observed them in the γ-ray spectrum gated by the 504 keV transition. Unfortunately, the 981 keV γ-ray angular distribution could not be correctly extracted because of the presence of the 988 keV γ line of ^{65}Zn. Another possibility is a $J = 4$ assignment (see Table I) if we allow a value of σ which does not obey the $\sigma = aJ + b$ relation established for the other spins. With this last assumption the 920 keV ($5^- \to 3^-$) and 981 keV ($5^- \to 4$) γ rays may have similar intensities. Thus we are not able to assign a

TABLE I. Results of the angular distribution measurements in ^{66}Zn.

E_γ	Transition	Angular distribution coefficients[a] A_2 ± 0.08	A_4 ± 0.14	σ_i	Fit parameters[b] $\alpha_2(J_i\sigma_i)$	$\alpha_2(J_f\sigma_i)$	δ	Multipolarity
1039.1	$2^+ \to 0^+$	0.294	−0.064	1.22	0.404	···	0	$E2$
1411.2	$4^+ \to 2^+$	0.30	−0.138	1.6	0.642	0.458	−0.017	$E2$
1296.4	$5^- \to 4^+$	−0.235	−0.025	1.8	0.69	0.642	−0.087	$E1$
328.2	$6^- \to 5^-$	−0.113	−0.038	2.0	0.71	0.69	0.075	$M1$
176.1	$7^- \to 6^-$	−0.139	0.007	2.2	0.745	0.71	0.058	$M1$
504.1	$7^- \to 5^-$	0.220	−0.186	2.2	0.745	0.69	−0.079	$E2$
1213.1	$9^- \to 7^-$	0.416	−0.013	2.6	0.777	0.743	−0.087	$E2$
1729.2	$6^+ \to 4^+$	0.290	−0.059	2.02	0.72	0.642	−0.105	$E2$
1026.1	$8^+ \to 6^+$	0.276	−0.131	2.45	0.755	0.72	−0.035	$E2$
1086.2	$10^+ \to 8^+$	0.416	−0.117	2.78	0.79	0.755	0.101	$E2$
954.7	$8^+ \to 7^-$	−0.266	−0.073	2.45	0.755	0.74	−0.045	$E1$
891.8	$4^+ \to 2^+$	0.214	−0.03	2.22	0.42	0.30	0	$E2$
	$3^+ \to 2^+$	0.214	−0.03	1.4	0.55	0.4	0.404	$M1/E2$
669.3	$5^- \to 4^+$	−0.356	−0.194	1.8	0.69	0.64	−0.132	$E1$
627.4	$4^+ \to 4^+$	0.179	−0.102	1.25	0.64	0.55	−0.25	$M1/E2$

[a] $W(\theta) = 1 + A_2 P_2(\cos\theta) + A_4 P_4(\cos\theta)$.

[b] Calculation performed using formula and notations of T. Yamazaki, Nucl. Data A3, 1 (1967). The alignment parameter α_2 is computed using a Gaussian substate population distribution of width σ.

definite J characteristic to the 2765 keV level, which is weakly populated in our experiment.

The 2826 keV state known as the 3_1^- level[7,11-13] is confirmed. The 3077 keV state has been observed as a 4^+ level[7,11,14,15]: we find that this state decays essentially to the 4_1^+ level by the 627 keV γ ray in agreement with Ref. 16, but in disagreement with Ref. 8. The angular distribution analysis of the 627 keV transition allows a $J=4$ assignment with correct values of α_2, but a too small value of σ according to the $\sigma = aJ + b$ relation (see Table I).

The 3746 keV state has been observed in the (p,p') reaction[17,18] and probably in the (α,α')[7] and (t,p)[11] reactions but the presence of other levels, very close in energy,[19] so far precluded a spin assignment. This level decays principally to the 4^+ states with the 1296 keV and 669 keV γ rays which are $L=1$ transitions: thus its spin is $J=3$, 4, or 5. The A_2 and A_4 values of the angular distribution coefficient exclude the $J=4$ assignment and we rule out the $J=3$ value for this state since none of the 2^+ states is fed from it; we propose $J=5$.

The 4250 keV state decays to the $J=5$ level by a cascade of two $L=1$ γ rays (176 keV and 328 keV)

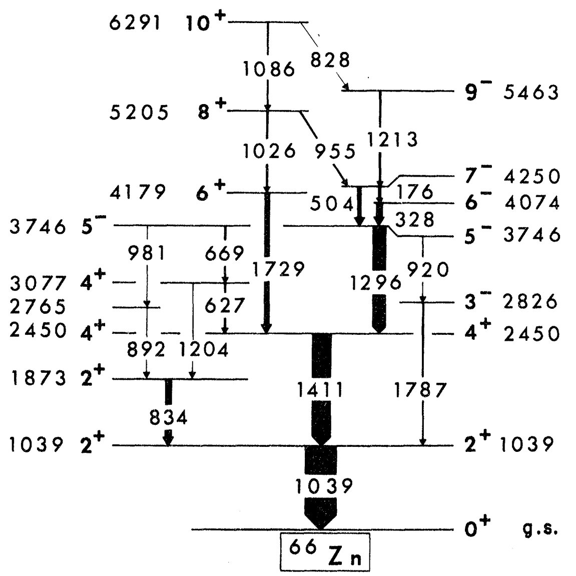

FIG. 3. Decay scheme of ^{66}Zn, obtained in measurements of γ-γ coincidences and yields. A few weak transitions are not presented here: the 953 keV γ ray (Ref. 15) which decays from the 3^- level at 2826 keV to the 2^+ level at 1873 keV; the 831 keV γ ray which decays from the 2704 keV level to the 1873 keV; the 1726 keV γ ray which decays from the 2765 keV level to the 1035 keV. Assignments of spin are based on yield functions, angular-distributions analysis, and no cross-over transition observations within a 5% intensity limit; for the degree of confidence see the text.

TABLE II. γ-ray energies and intensities in the ^{64}Ni-$(\alpha,2n)^{66}$Zn reaction at $E_\alpha = 27$ MeV.

Energy J^π Initial state		Final state		E_γ [a] (±0.5 keV)	Relative intensity [b] (±10%)
1039	2^+	g.s.	0^+	1039.1	100
1873	2^+	1039	2^+	834 [c]	20
2450	4^+	1039	2^+	1411.2	62
2704		1873	2^+	831 [c]	6
2765		1873	2^+	891.8	4
		1039	2^+	1726 [c]	3.5
		2450	4^+	316 [c]	<2 [d]
2826	3^-	1039	2^+	1787.5	6
3077	4^+	1873	2^+	1204 [c]	... [d]
		2450	4^+	627.4	9
3746	5^-	2450	4^+	1296.4	41
		2826	3^-	919.9	2
		3077	4^+	669.3	8.5
		2765		981.6	<2.5 [d]
4074	6^-	3746	5^-	328.2	27
4179	6^+	2450	4^+	1729 [c]	14
4250	7^-	4074	6^-	176.1	13
		3746	5^-	504.1	15
5205	8^+	4250	7^-	954.7	6.5
		4179	6^+	1026.1	5.5
5463	9^-	4250	7^-	1213.1	9
6291	10^+	5205	8^+	1086.2	4.5
		5463	9^-	828 [c]	<1

[a] Observed γ-ray energies, fitted using a quadratic energy calibration (Ref. 16).

[b] Measured at 90° to the beam direction.

[c] Energy determination: ±1 keV.

[d] γ ray observed in γ-γ coincidence. Unresolved in single-γ spectrum (doublet with 316 keV transition in ^{66}Cu).

[e] Probably doublet.

and by a crossover $L=2$ γ ray (504 keV); we can assign to it the value $J=7$ in agreement with the yield function slopes of the 504 keV and 176 keV γ rays. Furthermore, this level may be identified, with a good energy accuracy, with the (7^-) state observed in the (t,p) reaction,[11] so that we assign $J^\pi = 7^-$ to the 4520 keV level. Consequently, we exclude a positive parity for the $J=5$ state at 3746 keV, since the 504 keV γ ray thus would be an $M2$ transition, and a Weisskopf estimation, taking into account the branching ratios (54%, 46%) of the two γ rays (504 keV and 176 keV) which deexcite the 7^- level, gives in this case a half-life $T_{1/2} \gtrsim 30$ ns for the 7^- level, and we have not observed the 504 keV and 176 keV γ rays so delayed between beam bursts (it is well established[19,20] that a $M2$ transition cannot be accelerated). Thus we propose $J^\pi = 5^-$ for the 3746 keV level.

The 4074 keV state is obviously a $J=6$ state since the 176 keV and 328 keV γ rays are $L=1$ transitions and the absence of transition to the

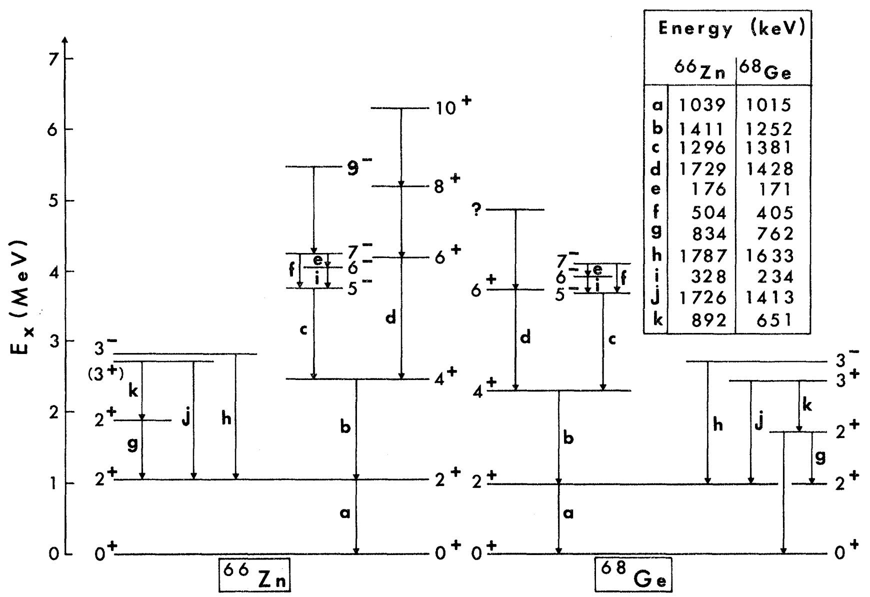

FIG. 4. Comparative decay schemes of $^{66}_{30}Zn_{36}$ and $^{68}_{32}Ge_{36}$, supporting the idea that the observed levels may be understood as neutron excited states.

4^+ levels allows the exclusion of a positive parity. We assign $J^\pi = 6^-$ to the 4074 keV level.

The 4179 keV state decays only to the 4^+_1 state through a $L = 2$ transition of 1729 keV: the absence of other line deexciting this level and the yield function of the 1729 keV γ ray favor the $J = 6$ assignment. In the hypothesis of a negative parity the transition to the 5^- state of 3746 keV should be competitive with the 1729 keV line, even if we assume the extreme value of 10^{-3} Weisskopf units (W.u.) for its strength. The absence of a transition to the 5^- state makes the assignment $J^\pi = 6^+$ more probable.

The 5205 keV is deexcited to the 6^+ level by a 1026 keV γ ray ($L = 2$) and to the 7^- level by a 955 keV γ ray ($L = 1$): the angular distributions analysis, the yield functions, and the branching ratio (54%, 46%) of these lines allow a $J^\pi = 8^+$ assignment.

The 5463 keV state decays only to the 7^- state by the 1213 keV ($L = 2$) γ ray. The absence of transitions to the 4^+, 5^-, 6^+, 6^- states exclude the values $J = 5$, 6, and 7 for this level and the yield function of the 1213 keV line indicate a $J > 7$. The value $J = 8$ may be removed since no transition to the 6^+ or 6^- was observed. Thus we propose the $J^\pi = 9^-$ assignment with a negative parity to take into account the fact that the 1213 keV γ ray is not delayed (it is not a $M2$ transition).

The 6291 keV state is mainly deexcited by the 1086 keV ($L = 2$) line to the 8^+. The same considerations as above allow $J = 9$ or 10 values. The 1086 keV angular-distribution analysis, the absence of transition to the 7^- state, and the relative weakness of the 828 keV transition to the 9^- state are coherent facts which assign $J = 10$ to the 6291 keV level. We propose $J^\pi = 10^+$, since the 1086 keV γ ray is not delayed (not $M2$).

IV. DISCUSSION

It will be noted that (i) our spin assignments are also supported by the increase of the alignment from the $J = 2$ to the $J = 10$ states (see the coefficients α_2 in Table I); (ii) the reaction $^{64}Ni(\alpha, 2n\gamma)$-$^{66}Zn$ mainly populates the so-called yrast states; thus the 3^-_1 state at 2826 keV, 4^+_1 state at 2450 keV and 5^-_1 state at 3746 keV are clearly observed, whereas the 4^+ at 3077 keV is more weakly populated and the 3^-_2 (at 4395 keV)[11] and the 5^-_2 (at 3899 keV)[11] are not seen.

It is difficult to obtain a theoretical understanding of these experimental results due to the large number of particles outside the closed shell ($8n$, $2p$) which make any calculation very complex. However, if we compare the level schemes of the isotonic nuclei ^{66}Zn and ^{68}Ge (Ref. 21, Fig. 4), we may suppose that the observed states common to both nuclei are neutron excited states. Thus we may speculate that positive-parity states are associated with the $\nu[(1f_{5/2})^2\,(1g_{9/2})^2]^J$ configurations and negative-parity states are associated with the $\nu[(1f_{5/2})^2_{0^+}(1f_{5/2}1g_{9/2})]^J$ configurations up to $J^\pi = 7^-$ and $\nu[(1f_{5/2})^3(1g_{9/2})]^J$ configurations beyond $J^\pi = 7^-$. This speculation, based on a few-nucleon excitation, is supported by recent lifetime measurements in ^{68}Ge (Refs. 22, 23) in which the enhancement of the 405 keV γ ray ($7^- \rightarrow 5^-$) is found to be only 4 W. u. indicating that there are no strong collective effects.

A sensitive test of the wave functions of nuclear states is provided by the data on radiative lifetimes, but at present lifetimes in ^{66}Zn are known only for the lowest levels[16, 24]; such measurements, by the recoil-distance method, are foreseen in the near future.

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