Université Scientifique et Médicale de Grenoble

INSTITUT DES SCIENCES NUCLEAIRES
DE GRENOBLE

53, avenue des Martyrs - BP 257 ● 38044 Grenoble Cedex
Tél. 87 71 41

FR7600705

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HIGH-SPIN LEVELS IN ^{60}Zn

J.F. BRUANDET, M. AGARD, A. GIORNI, J.P. LONGEQUEUE, C. MORAND,
TSAN UNG CHAN

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High Spin States in ^{66}Zn

J.F. Bruandet, M. Agard, A. Giorni, J.P. Longequeue, C. Morand, Tsan Ung Chan

Institut des Sciences Nucléaires, B.P. 257 Centre de Tri

38044 Grenoble Cedex, France

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 10 ħ were assigned to observed states.

NUCLEAR REACTIONS ^{64}Ni(α,2nγ)^{66}Zn, 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 $J^\pi = 9/2^+$ 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 $1\,g_{9/2}$ shell [1]. The neutron $1\,g_{9/2}$ shell is thus not far removed in energy from the $1\,f_{5/2}$ shell and consequently, among the states at a few MeV excitation in ^{66}Zn one may expect those whose 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,2nγ) reactions or (HI,xn yp z α) reactions [2,3]. This is readily understandable since the notion of "high spin" in the f-p shell essentially 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 favouring 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,2nγ) and ^{64}Zn(α,2pγ) reactions using α particles of 22-40 MeV and subsidiary measurements were also made using the reactions ^{63}Cu(α,pγ) at 22 MeV, ^{65}Cu(α,p2nγ) at 40 MeV, ^{68}Zn(α,α2nγ) at 40 MeV and ^{56}Fe(^{12}C,2pγ) at 40 MeV. The ^{64}Ni(α,2nγ) 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,3nγ)^{65}Zn reaction is completely eliminated and the only competing channel is the ^{64}Ni(α,pn)^{66}Cu reaction in which the desintegration 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) [illegible].

(2) Evaporation of neutrons was preferred to [illegible] for the reasons outlined above. We performed [illegible] angular distributions at E_α = 30 MeV for a better yield of the high spin levels.

Using beams from the Grenoble cyclotron, an [illegible] (99.7 %) self supporting ^{64}Ni target (700 μg/cm^2) and large volume Ge(Li) detectors (80 - 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 : Fig. 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 α_2 (J) for each level, which remains nearly constant for all transitions to [illegible], the corresponding χ^2 being very close to its minimum value. We further note that, with our assignment the parameters σ and the spin J of a given level are [illegible] related through the relation σ = a J + b where a and b are positive constants (with one exception for the 627 keV transition).

– Delayed γ rays [illegible] bursts (ν_{HF} = 13.9 MHz at E_α = 50 MeV) : [illegible] between 5 and 100 ns were [illegible]. A [illegible] delayed γ ray ($T_{1/2}$ = 17 ± 2 ns) [illegible] transition deexciting the [illegible] keV level in ^{66}Zn (Fig. 3) since the [illegible] γ-rays is not delayed ; the origin of this transition may be found in the parasitic reaction ^{64}Ni(α,αn)^{63}Ni. It will be noted that no other delayed transitions have been observed in 5 to 100 ns time range.

III - SYNTHESIS OF RESULTS

Referring to Fig. 2-3 and Tables I-II we now discuss spin and parity assignments.

The 2^+ states at 1039 keV and 1872 keV are well known.

The 2450 keV state : the assignment 4^+ [5,6,7] is confirmed.

The 2765 keV state : this level has been observed in the (p,p'γ) reaction[6] 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 320 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 808 keV γ-line of ^{64}Zn. Another possibility is a J = 4 assignment (see table 2) if we allow a value of σ which does not obey the σ = a J + b relation established for the other spins. With this last assumption the 920 keV ($5^- \rightarrow 3^-$) and 1584 keV ($5^- \rightarrow 4$) γ rays may have similar intensities. Then we are not able to assign a definite J characteristic to the [illegible] keV level which is weakly populated in our experiment.

The 2826 keV state known as the 3^-_1 level [7,11,12,13] 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 a_2 but too small value of σ referring to the σ = a J + b relation (see Table 1).

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 1295 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) and by a cross-over L = 2 γ-ray (504 keV) : we can assign to it the value J = 7 in agreement with the yield functions 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 4250 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 a

M2 transition and a [illegible] [illegible] ratio (54 %, 46 %) of the two γ rays (5[illegible] keV and [illegible] keV) which de-excite the 7^- level, gives in this case a half life $T_{1/2} \geq 30$ ns for the 7^- level and we have not observed the 5[illegible] keV and [illegible] keV [illegible] delayed (it is well established[19,20] that a M2 transition cannot be accelerated). Thus we propose $J^\pi = 5^-$ for the [illegible] level.

The 4074 keV [illegible] indicating the 17[illegible] keV and 320 keV γ-rays are L = 1 transitions [illegible] of transition to the 4^+ levels allows the exclusion of [illegible]. 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 lines [illegible] this level and the yield function of the 1729 keV γ-ray favour the J = 6 assignment. In the hypothesis of a negative parity the transition to the 5^- state of 3[illegible] keV should be competitive with the 1729 keV line, even if we [illegible] the extreme value of 10^{-3} 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 [illegible]$^+$ level by a 3[illegible] keV γ-ray (L = 2) and to the 7^- level by a 555 keV γ ray (L = 1) : the angular distribution analysis, the yield functions and the branching ratio (54 %, 46 %) of these lines allow a $J^\pi = 6^+$ 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, 7 for this level and the yield function of the 1213 keV line indicate a J > 7. The value J = 8 may be [illegible] 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 [illegible] keV state is mainly [illegible] by the [illegible] keV (L = 2) line to the 8^+. Same considerations than above allow J = [illegible] or 10 values. The [illegible] keV angular distribution analysis, the absence of transition to the 7^- state, and the relative weakness of the 878 keV transition to the 5^- state are coherent facts which assign J = 10 to the [illegible] level. We propose $J^\pi = 10^+$ since the [illegible] keV γ-ray is not delayed ([illegible]).

IV - [illegible]

It will be noted that : (i) our spin assignments are [illegible] supported by the increase of the alignment from the J = 2 to [illegible] (see the coefficients a_2 in Table I) (ii) the reaction [illegible] only populate the so called yrast states : thus the 3^-_1 state at [illegible] keV, 4^+_1 state at 2450 keV and 5^-_1 state at [illegible] keV are [illegible] the 4^+ at 3077 keV is more weakly populated and the 3^-_2 ([illegible] keV)[11] and the 5^-_2 (at 3899 keV)[11] are not seen.

It is difficult to obtain a theoretical [illegible] of these experimental results due to the large number of particles outside the closed shell (6n,2p) which make any calculation very complex. However, [illegible] the level schemes of the isotonic nuclei ^{66}Zn and ^{68}Ge [11] ([illegible]), [illegible] that the observed states common to both nuclei are [illegible]. Thus we may speculate that positive parity states are associated with the $\nu\left[(1\,f_{5/2})^2\,(1\,g_{9/2})^2\right]^J$ and negative parity states are associated with the $\nu\left[(1\,f_{5/2})^2\ \text{or}\ (1\,f_{5/2}\ 1\,g_{9/2})\right]^J$ configurations up to $J^\pi = 7^-$ and $\nu\left[(1\,f_{5/2})^3\,(1\,g_{9/2})\right]^J$ configurations beyond $J^\pi = 7^-$. This speculation, based on a few nucleon excitation, is supported by recent lifetime measurements in ^{66}Zn [illegible] moment of the 405 keV γ-ray ($7^- \to 5^-$) is found to be only [illegible] 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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TABLE 1. Results of the angular distribution measurements in ^{66}Zn

E_γ	Transition	Angular distribution coefficients [a]		Fit parameters [b]				Multipolarity
		A_2 ± 0.08	A_4 ± 0.14	σ_i	$\alpha_2(J_i\sigma_i)$	$\alpha_2(J_f\sigma_f)$	δ	
1039.1	$2^+ \to 0^+$	0.295	-0.064	1.22	0.404	-	0	E2
1411.2	$4^+ \to 2^+$	0.30	-0.135	1.6	[illegible]	[illegible]	-0.017	E2
1296.4	$5^- \to 4^+$	-0.235	-0.025	1.8	[illegible]	[illegible]	[illegible]	E1
328.2	$6^- \to 5^-$	-0.113	-0.03[illegible]	2.0	0.71	0.69	0.075	M1
176.1	$7^- \to 6^-$	-0.159	[illegible]	[illegible]	[illegible]	0.71	[illegible]	M1
504.1	$7^- \to 5^-$	0.250	-0.186	2.2	[illegible]	[illegible]	[illegible]	E2
1213.1	$9^- \to 7^-$	0.416	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	E2
1729.2	$6^+ \to 4^+$	0.290	-0.059	2.02	0.72	0.632	-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	0.76	-0.055	E1
891.8	$4^+ \to 2^+$	0.214	-0.03	2.22	0.52	[illegible]	0.	E2
	$3^+ \to 2^+$	0.214	-0.03	1.4	0.55	[illegible]	0.404	M1/E2
669.3	$5^- \to 4^+$	-0.356	-0.194	1.8	[illegible]	0.64	-0.132	E1
627.4	$4^+ \to 4^+$	0.179	-0.102	1.25	0.64	[illegible]	-0.25	M1/E2

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

[b] Calculation performed using formulae and notation of T. Yamazaki, Nucl. Data, Sec A3, 1 (1967). The alignment parameters α_2 [illegible] a Gaussian substate population distribution of width σ.

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

Energy	J^{π}	Energy	J^{π}	E_{γ}[a]	Relative intensity[b]
Initial	state	Final	state	(keV)	(%)
1039	2^+	GS	0^+	[illegible]	[illegible]
1873	2^+	1039	2^+	[illegible] [*]	20
2450	4^+	1039	2^+	1411.2	62
2704		1873	2^+	[illegible] [*]	6
2765		1873	2^+	[illegible]	4
		1039	2^+	[illegible] [*]	[illegible]
		2450	4^+	316	< 2 [c]
2826	3^-	1039	2^+	[illegible]	6
3077	4^+	1873	2^+	[illegible] [*]	– [d]
		2450	4^+	627.7	9
3746	5^-	2450	4^+	[illegible]	41
		2826	3^-	[illegible]	2
		3077	4^+	[illegible]	[illegible]
		2765		[illegible]	< 2.5 [d]
4074	6^-	3746	5^-	[illegible]	27
4179	6^+	2450	4^+	[illegible] [*]	14
4250	7^-	4074	6^-	[illegible]	15
		3746	5^-	[illegible]	15
5205	8^+	4250	7^-	954.7	6.5
		4179	6^+	[illegible]	5.5
5463	9^-	4250	7^-	1213.1	9
6291	10^+	5205	8^+	[illegible]	4.5
		5463	9^-	828 [*]	< 1

[a] Observed γ-ray energies, fitted using a quadratic energy calibration [26]

[b] Measured at 90° to the beam direction

[c] γ-ray observed in γ-γ coincidence, unresolved in single-γ spectrum (doublet with 316 keV transition in ^{66}Ga)

[d] Probably doublet

[*] Energy determination ± 1 keV

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Figure Caption

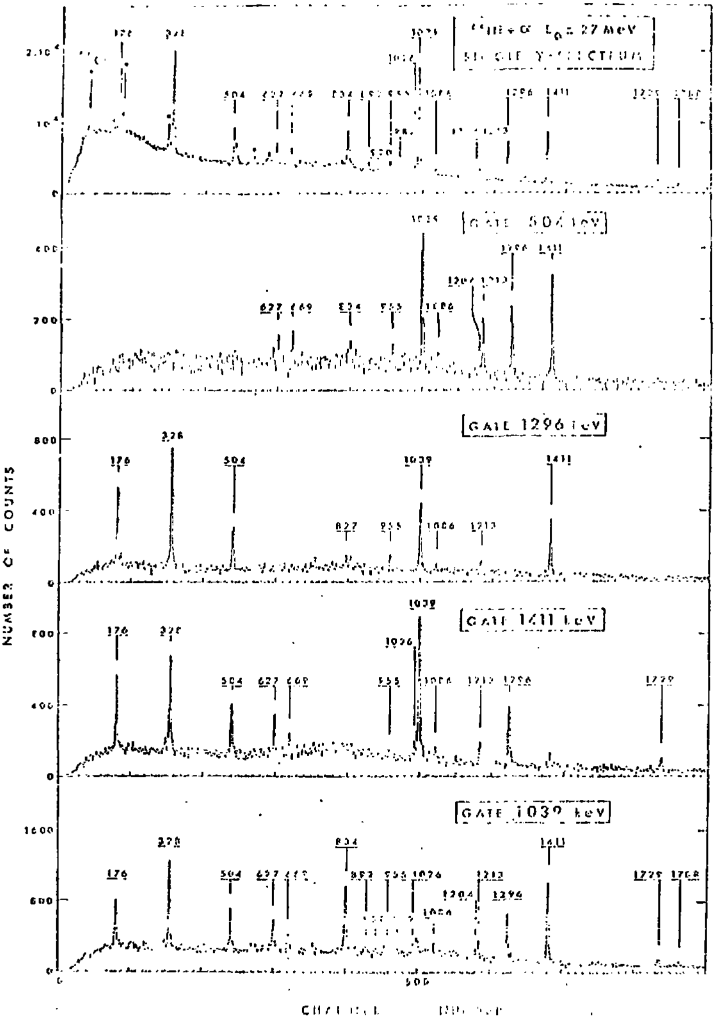
FIG. 1 Upper part : [illegible] target with 27 MeV α particles. Precise γ-ray energies are given in table I.

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 (α, 2n)^{66}Zn reaction. Intensities are [illegible] to the 1039 KeV transition. The 1723 KeV γ-ray is unresolved at E_{α} = 40 MeV.

FIG. 3 Decay scheme of ^{66}Zn, obtained in measurements of γ-γ coincidences and yields. Few weak transitions are not presented here : the 95[illegible] KeV γ-ray [25] 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 level at 2765 KeV to the 1039 KeV level. Assignments of spin are based on yield functions, angular distributions analysis and no crossover transitions observations within a 5% intensity limit : for the degree of confidence see the text.

FIG. 4 Comparative decay schemes of $^{66}_{30}$Zn$_{36}$ and $^{68}_{32}$Ge$_{36}$ suggesting the idea that the observed levels can be understood as neutron excited states.


E₀ = 27 MeV
SINGLE γ-SPECTRUM
2.10⁴
10⁴
0
176
226
504
627
669
834
892
955
1026
1039
1086
1213
1296
1411
1729
1768
GATE 504 keV
600
200
0
627
669
834
955
1035
1086
1204
1213
1296
1411
GATE 1296 keV
800
400
0
176
226
504
827
955
1039
1086
1213
1411
GATE 1411 keV
800
400
0
176
226
504
627
669
955
1026
1039
1086
1213
1296
1729
GATE 1039 keV
1600
800
0
176
226
504
627
669
834
892
955
1026
1086
1204
1213
1296
1411
1729
1768
NUMBER OF COUNTS
0
500
CHANNEL NUMBER

Ge(Li) detectors.

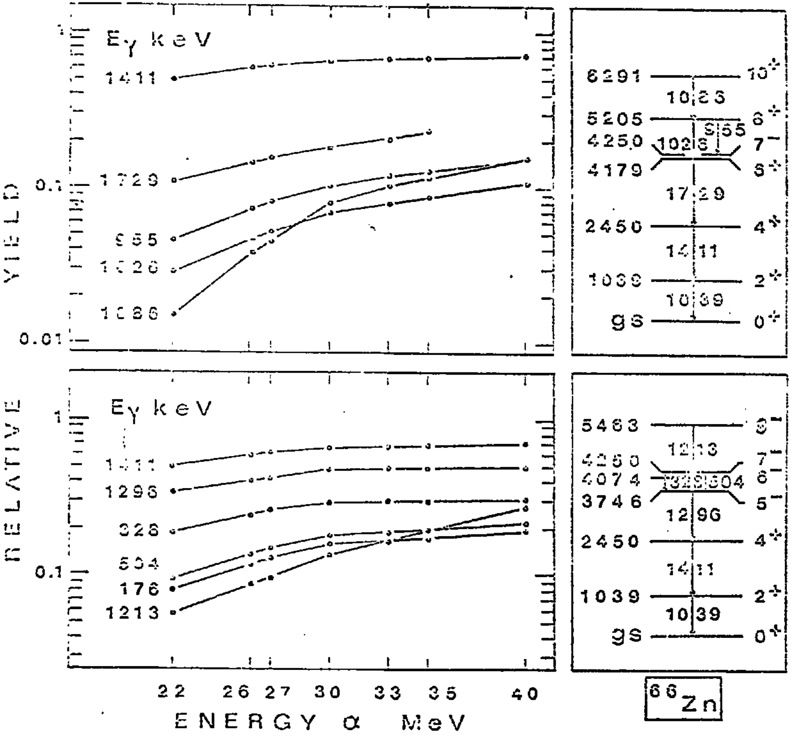
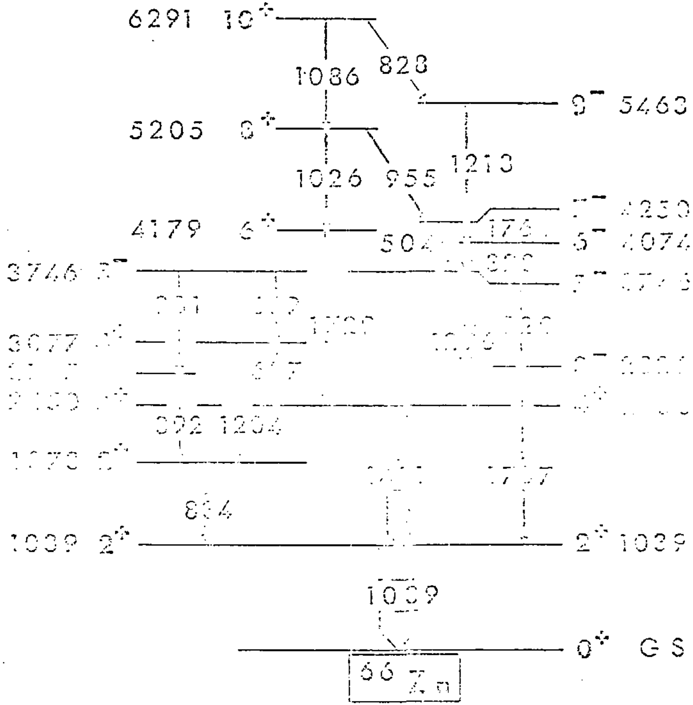


Fig 2


6291 10+
1086
828
9− 5463
5205 8+
1026
955
1213
4179 6+
504
174
5− 4074
3746
1039 2+
2+ 1039
1039
0+ GS
66 Zn
392
1204
834

[illegible]

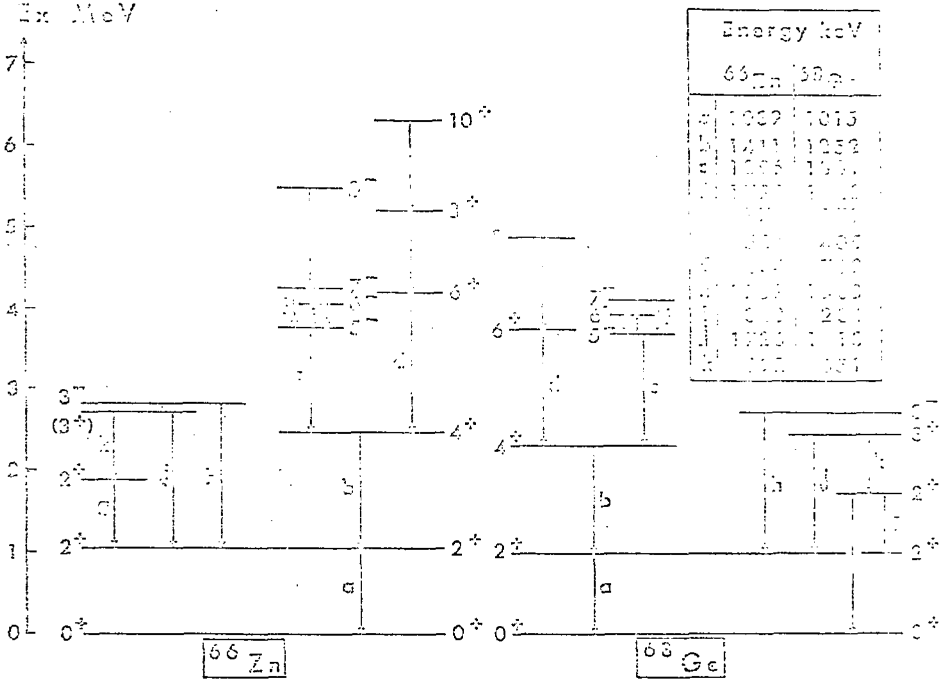


Fig. 4

χ^2 being very close to the minimum value, [illegible] with our assign