The Level Structure of ^{64}Zn Through the ^{63}Cu(p, γ)^{64}Zn Reaction*

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The excited states of the ^{64}Zn nucleus was investigated in the ^{63}Cu(p,γ)^{64}Zn reaction. By means of the Ge(Li)-NaI(Tl) coincidence measurement, the level scheme of ^{64}Zn was established and for a number of levels the spin-parity assignments were suggested on the basis of the measured γ-branching ratios. The theoretical calculation in the framework of the conventional shell model was compared with the experimental result and discussed.

I. INTRODUCTION

IN recent years (p,γ) reactions have been widely used for experimental studies of nuclear level structure, and there were many data of (p,γ) reactions that have been reproduced in many laboratories when the high-resolution detector of Ge(Li) for r-ray was available. The experimental works of the (p,γ) reactions on light and medium-weight nuclei with use of a 50$-$cm^3 Ge(Li) detector in this laboratory have been extensively investigated to study the level scheme for several years, and the works on aluminium and arsenic isotopes have been- completed and published or to be published.[1-3]

Concerning nuclear level structure of ^{64}Zn, most informations were obtained from ^{64}Zn($p, p'\gamma$)[4], Zn^{64}(d, d')[5] and B-decay from ^{64}Ga by means of the ^{64}Zn(p, n)^{64}Ga reaction.[6] The work on the ^{63}Cu(p, γ)^{64}Zn reaction, however, was rarely being reported except the work of Weller and Grosskreutz[7] in 1956. In their investigation, the experimental work was carried out with poor energy resolution of the NaI(Tl) detector. In the present study of the ^{63}Cu(p, γ)^{64}Zn reaction, a detailed decay scheme of ^{64}Zn was constructed from the analysis of the measured r-ray spectrum and the energy levels of ^{64}Zn up to about 4 MeV excitation energy were accurately determined. The spins-parities of a resonance

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of de-excitation at E_p=2098 keV and the observed energy levels in ^{64}Zn were discussed and compared with the theoretical shell-model calculation in which a truncated model space with restriction of the low-seniority configuration was assumed. The result of the calculation is described on Section IV.

II. EXPERIMENTAL METHOD AND RESULTS

The proton beams were accelerated by the 3 MV Van de Graaff at Tsing Hua University, and the energy resolution of the beams were estimated to be 0.1%. A 99.4% enriched target of ^{63}Cu was prepared by evaporating on a 99.99% gold backing and its thickness was estimated to be 30 $\mu g/cm^2$. A 7.6~ 7.6 cm NaI(T1) detector was fixed at 90 " to the proton beam to measure the excitation functions for r-rays of energy E_r=992 keV and E_r>7500 keV. The proton energy was varied from E_p=1750 to 2950 keV in steps of l-and 2 keV around and off the resonance, respectively. The decaying spectrum of the resonance at E_p=2098 keV, corresponding to the excitation energy E_{ex}=9772 keV in ^{64}Zn, was measured with a 50-cm^3 Ge(Li) detector at -90 " to the beam direction. A Ge(Li)-NaI(T1) coincidence measurement shown in Fig. 1 was also used for determining the relative intensities and the corresponding transitions of the higher excited levels in ^{64}Zn. The relationships between the Ge(Li) and NaI(T1) detectors in the coincidence measurement is listed in Table I. The r-energies were calibrated by the standard sources of r-ray for the energy region <3000

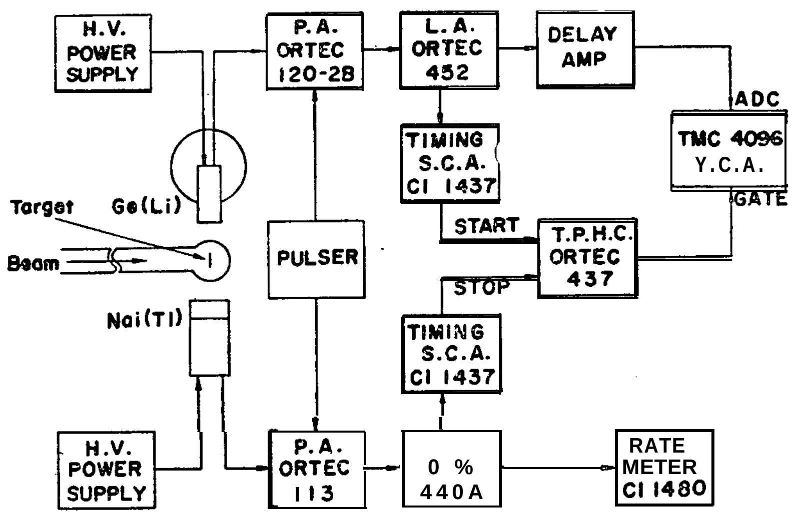

Fig. 1. Block diagram of a Ge(Li)-NaI(T1) coincidence measurement

Table I. The relationships between the Ge(Li) and NaI(T1) detectors in the coincidence measurement

γ-ray energy selected as the gate in the NaI(Tl) detector (keV)	Coincidence r-ray observed in the Ge(Li) detector (keV)
$6480<E_r<6980$	$500<E_r<3300$
$6000<E_r<6500$	$1500<E_r<3700$

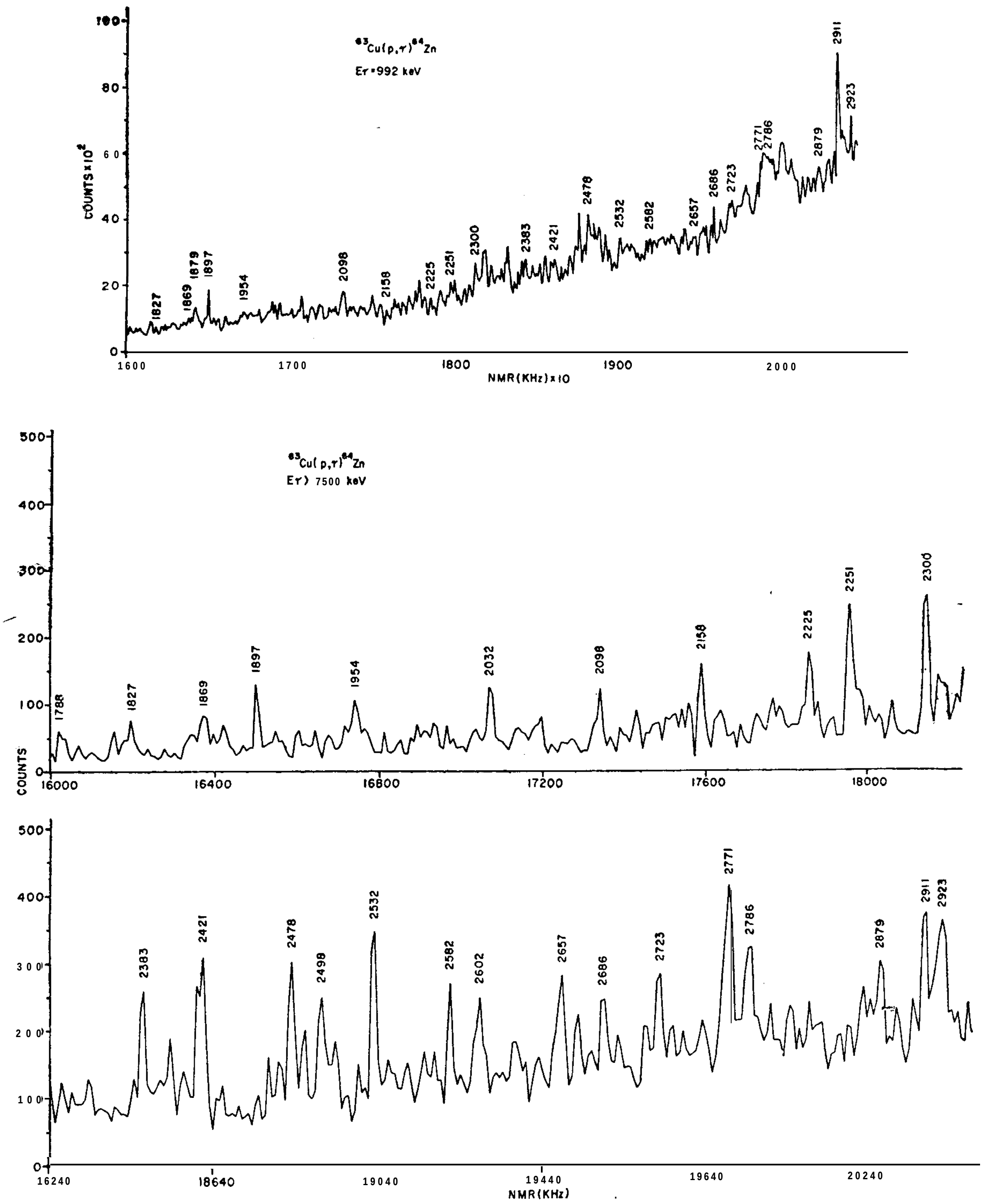

Fig. 2. The excitation functions of 992 keV γ-ray and larger than 7500 keV γ-rays. The numbers refer to the proton energy (in keV) of the resonance.

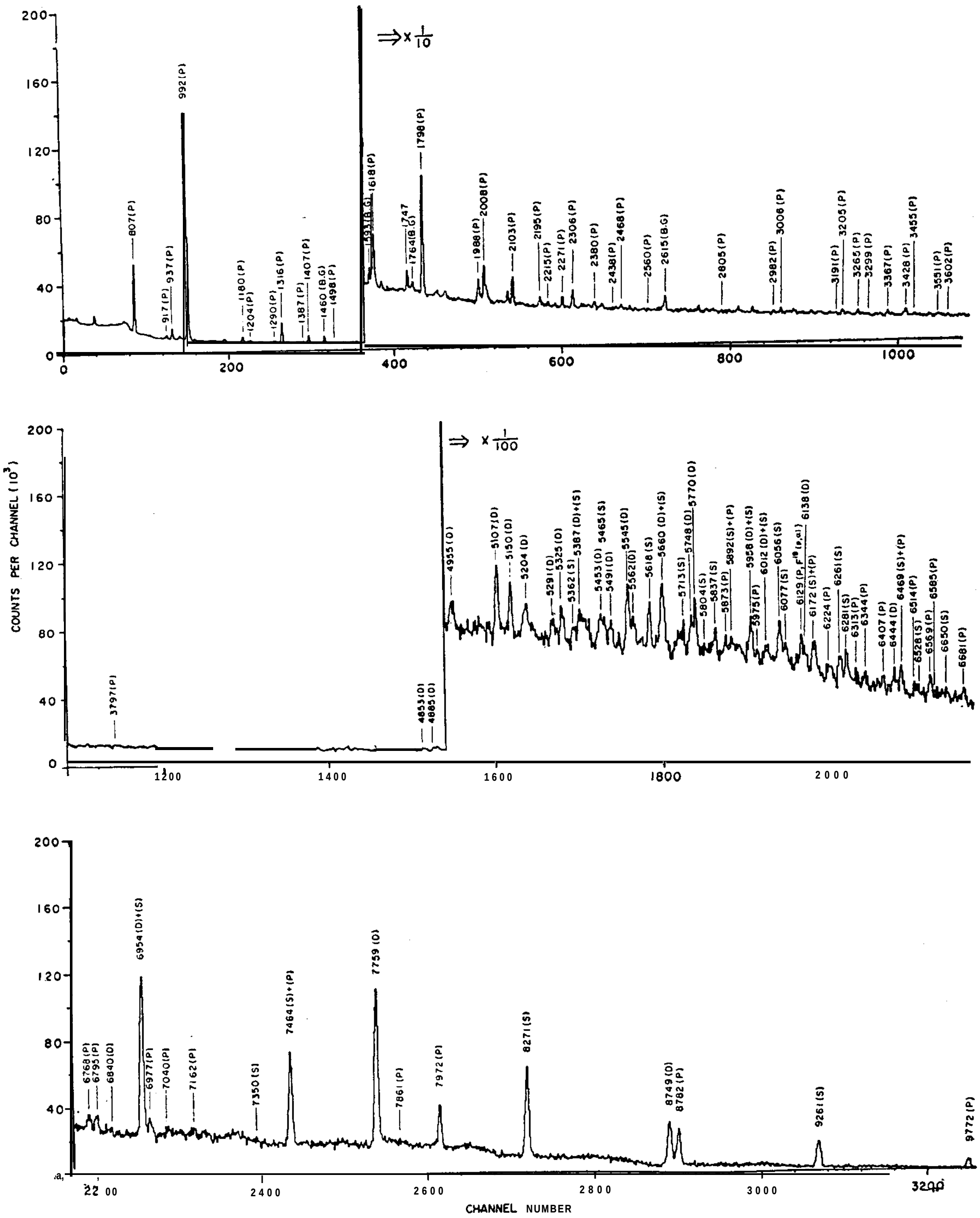

Fig. 3. A decay spectrum of the resonance at E_p=2098 keV. The number, P, S and D refer to the energy of the γ-ray (in keV), photo peak, single escape and double escape peak, respectively.

keV, and the 6129 keV contaminant r-ray from the $^{19}F(p,\alpha\gamma)^{16}O$ reaction, and its single and double escape peaks for higher energy portion. The relative efficiency of the Ge(Li) detector determined in the present analysis was similar to those described previously.[1-3] Fig. 2 shows the excitation functions of $E_\gamma=992$ keV and $E_\gamma>7500$ keV. Fig. 3 shows a decay spectrum of the resonance at $E_p=2098$ keV. The energies of the r-rays observed in Fig. 3, the relative

Table II. r-ray energies, and relative intensities from the resonance of de-excitation at $E_p=2098$ keV in the $^{63}Cu(p,\gamma)^{64}Zn$ reaction. The symbol $\gamma\to0$ refers to the transiton from the resonance to the ground state and the symbol $\gamma\to992$, for example, refers to the transition from the resonance to the 992 keV state in ^{64}Zn

γ-ray energy (photo peak) (keV)	Relative intensity	Corresponding transition in ^{64}Zn	γ-ray energy (photo peak) (keV)	Relative intensity	Corresponding transition in ^{64}Zn
9772	24.91t4.5	γ→0	3205	4.0± 1.1	3206→0
8782	69.6f6.3	γ→992	3191	4.1±0.8	3188→0
7972	65.3±20.0	γ→1799	3006	3.0 f-o.5	3004→0
7861	7.0±0.5	γ→1909	2982	0.8f0.3	2980→0
7464	10.5f4.0	γ→2308	2805	2.5zko.4	3797→992
7162	5.5f2.0	γ→2610	2560	3.1f1.2	3549→992
7040	6.8± 1.8	γ→2736	2468	2.5zt0.3	3458→992
6977	12.0± 1.0	γ→2794	2438	1.340.5	3428→992
6795	14.6± 1.8	γ→2980	2380	4.2f1.3	3368→992
6768	14.5± 1.0	γ→3004	2306	10.6±1.5	3300→992
6681	15.3f3.6	γ→3092	2271	5.8h0.4	3263→992
6585	8.7±0.9	γ→3188	2215	3.6±0.5	3206→992
6569	13.7±1.5	γ→3206	2195	8.0±0.9	3188→992
6514	5.8±2.0	γ→3263	2103	11.9±1.1	3092→992
6469	11.2±3.0	γ→3300	2008	26.644.7	3004→992
6407	8.0f2.0	γ→3368	1988	10.4±3.2	2980→992
6344	S.6f1.6	γ→3428	1798	49.3±2.7	1799→0
6313	7.8f3.0	γ→3458	1747	6.5zkO.5	2736→992
6224	12.2 ± 1.6	γ→3549	1618	3.8±0.3	2610→992
6172	7.7±3.0	u-3602	1498	3.1±1.2	3300→1799
5975	7.7±1.8	γ→3797	1407	3.0±1.0	3206→1799
5892	6.5±3.1	γ→3874	1387	2.7±0.6	3188→1799
5873	5.2zkl.l	γ→3900	1316	13.2zk2.1	2308→992
3797	7.2f2.1	3797→0	1290	4.7±0.2	3092→1799
3602	2.0±0.8	3602→0	1204	6.0zt0.4	3004→1799
3551	1.6f0.6	354940	1180	4.2f0.5	2980→1799
3455	4.3f2.0	3458→0	992	362.3± 10.9	992→0
3428	9.9±1.0	3428→0	937	4.240.2	2736-31799
3367	4.7±0.4	3368→0	917	8.2f0.7	1909→992
3299	4.5±2.0	3300→0	807	115.6f9.8	1799→992
3265	5.2 f0.6	3263→0			

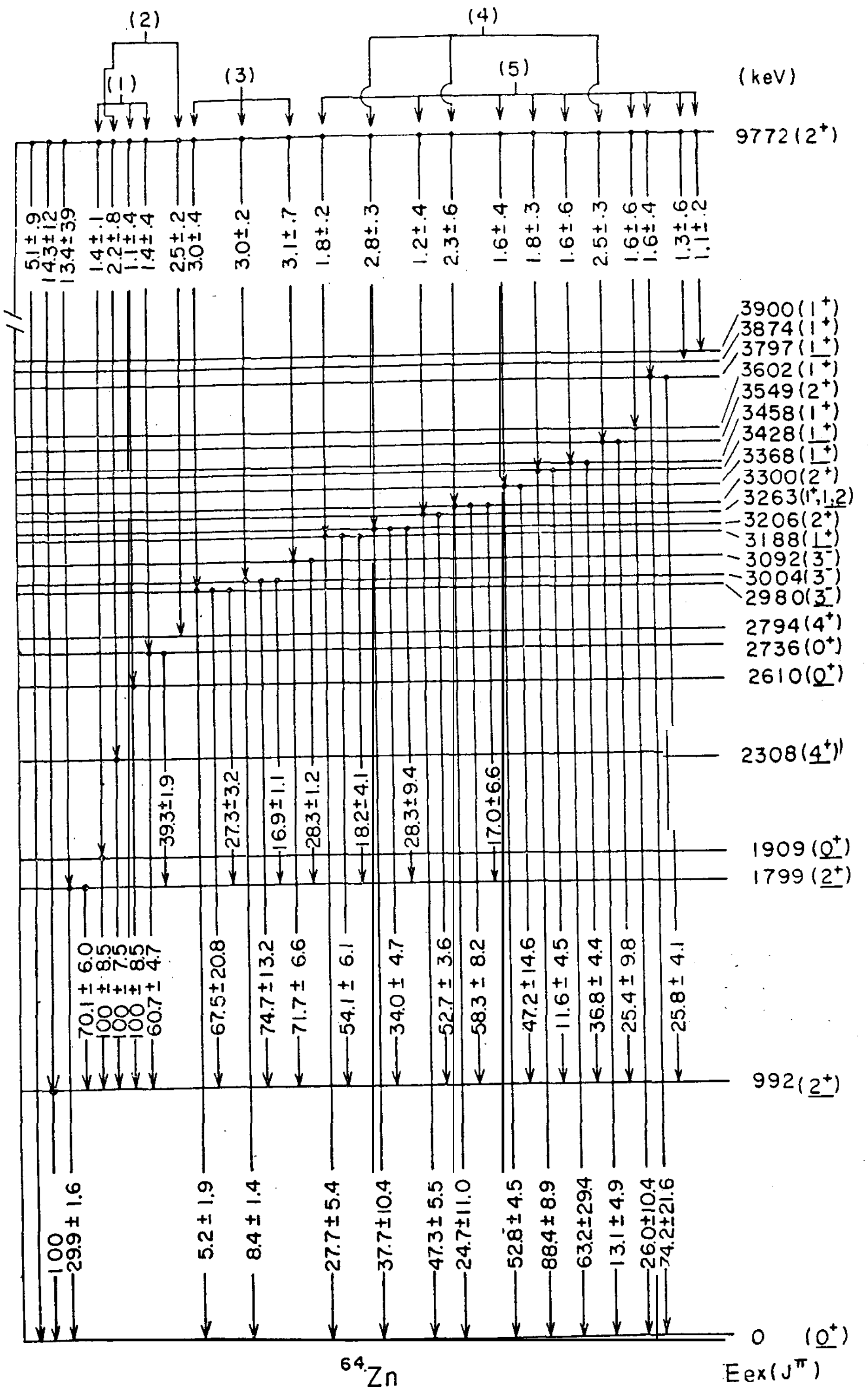

Fig. 4. The decay scheme of ^{64}Zn constructed from the resonance of de-excitation at 9772±2 keV (E_p=2098 keV). The numbers refer to the percentage of the branching ratio normalized by the intensity of 992 keV r-ray. Five characteristic groups are denoted as the (1), (2), (3), (4) and (5) on the top of the scheme. The J^π with a bar underneath are taken from Refs. 4-6, while the J^π without bar are suggested by the present experiment.

intensities and the corresponding transitions in ^{64}Zn are listed in Table II. The spectrum contains many unresolved weak peaks, we therefore listed only those transitions which could be indentified in the spectrum. The decay scheme of ^{64}Zn constructed from the resonance of de-excitation at excited energy of 9772-F-2 keV (E_p=2098 keV) is shown in Fig. 4. The branching ratios for r-rays decayed from the ^{63}Cu(p,γ)^{64}Zn reaction were not previously reported. We have determined in the present measurement the branching ratios for many transition lines. The numbers on the transition line in Fig. 4 refer to the percentage of the branching ratio normalized by the intensity of 992-keV r-ray. It is noted that the branching ratios for some particular levels are not completely determined due to the contaminant of natural background. Since the energies of the transitions from the 1799-and 992-keV states to the ground state are respectively the same as that from the 2794-to 992-and 1799-keV states, and also the same as that from the 3602-keV to 1799-keV state, the branching ratios for these transitions can not be obtained.

III. DISCUSSION

The resonance, r, of de-excitation at the energy of E_{ex}=9772 keV in ^{64}Zn was found to decay intensively into the excited states at E_{ex}=1799 (2^+) and 992 keV (2^+). If we assume that the most intensive transitions to be El or Ml, the spinparity of the resonance is likely to be ($1^{\pm}, 2^{\pm}, 3^{\pm}$). Since E3 or M3 transitions from the resonance of de-excitation is too weak to be observed, the ratio of the strength of $r\rightarrow$992$-$keV (2^+) to that of ground state (0+) is reasonably more close to the ratio Ml/E2 than that of any other decay mode, the spinparity of the resonance is therefore favourally to be 2^+ out of the ($1^{\pm}, 2^{\pm}$, and 3'). For the spins-parities of the excited levels in ^{64}Zn, we observed five characteristic groups among the measured branching ratios for r-ray transitions from the resonance of de-excitation, they are:
(1) $r\rightarrow$1909 (O+), 2610 (0+) and 2736 keV; (2) $r\rightarrow$2308 (4^+) and 2794 keV; (3) r-+2980 (3^-), 3004 and 3092 keV; (4) $r\rightarrow$3206, 3300 and 3549 keV; (5) $r\rightarrow$3188 (1^+), 3263 (1, 2), 3368 (1^+), 3428 (1^+), 3458, 3602, 3797 (1^+), 3874 and 3900 keV. Every group has about the same branching ratio corrected by its r-ray energy. By considering the final states in every group having the same spins and parities, the spins-parities of the following excited states can be suggested: 2736 keV (0^+); 2794 keV (4^+); 3004 keV (3^-); 3092 keV (3^-); 3263 keV (1^+); 3458 keV (1^+); 3602 keV (1^+); 3874 keV (1^+) and 3900 keV (1^+). Next, if we compared the ratios, which are respectively the strength of the levels at E_{ex}=3206, 3300 and 3549 keV feeding to the level at E_{ex}=992 keV (2^+) to that of those levels feeding to the ground state (0^+), with the ratio of the strength of any two possible decay modes, we found that the ratio of Ml/E2 is the most probable, thus the spins and parities of the group (4), i.e. the levels at E_{ex}= 3206, 3300 and 3549 keV, are likely to bo be 2^+.

IV. SHELL-MODEL CALCULATION

Since the theoretical discussions for ^{64}Zn have not yet been found in the literature, it is interesting to carry out a shell-model calculation of the normal-parity states for ^{64}Zn to compare with the present experimental results. In this calculation, the eight valence nucleons outside the ^{56}Ni core are assumed to be distributed among the $2p_{3/2}, 1f_{5/2}$, and $2p_{1/2}$ single-particle orbits. Due to the size of the model space in these orbits being massive, a truncated model space with restriction of the low-seniority configurations ”) is assumed. In the present calculation, the seniority numbers of basic states of ^{64}Zn are restricted UP to 2. With this restriction, the largest dimension of the matrix is reduced to 98 for $J=2$. The two-body residual interaction matrix elements of $T=0$ and $T=1$ are adopted respectively from the previous studies of copper[8] and Nickel[9] isotopes.

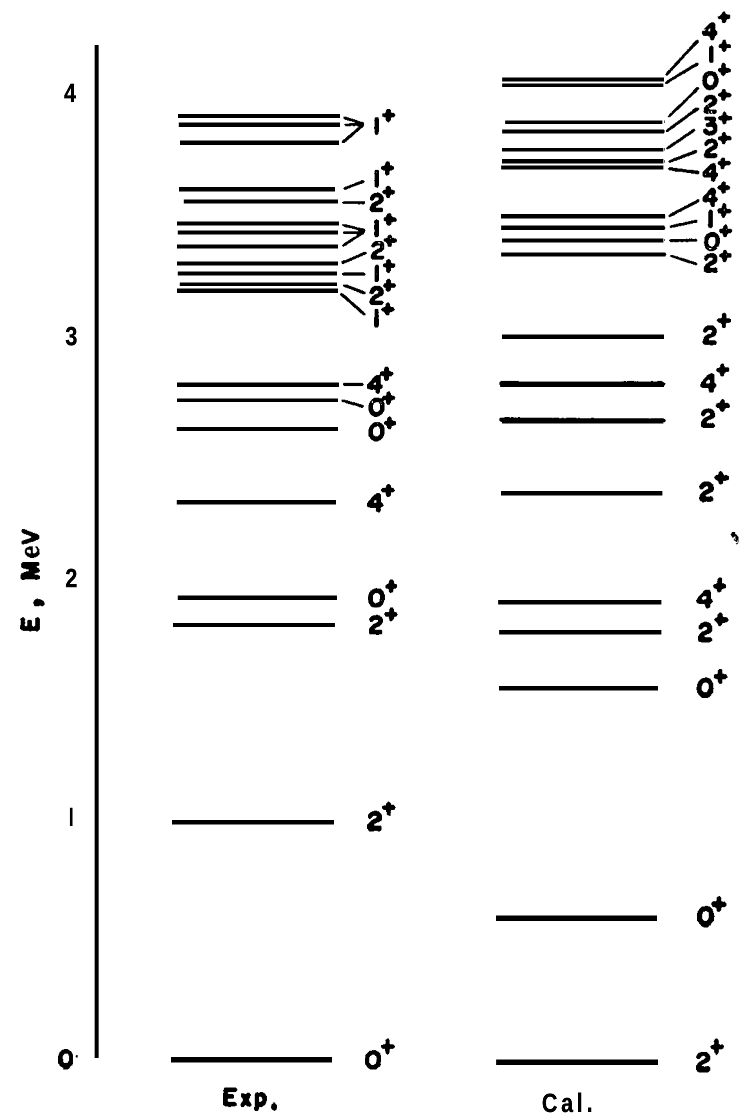

Fig. 5. Level scheme of ^{64}Zn from the present experiment and the shell-model calculation

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The single-particle energies of $1f_{5/2}$ and $2p_{1/2}$ orbits relative to $2p_{3/2}$ orbit are varied to give a best fit between the theoretical calculation and the lowest five observed levels. The final set of single-particle energies which we used to obtain the results are given in MeV as follow: $1f_{5/2}$, 0.396; $2p_{1/2}$, 0.989; where the energy of the $2p_{3/2}$ is set to be zero. The energy levels calculated with this model are compared with the -present experimental energy levels as shown in Fig. 5. Although the lowest two pairs of 0^+ and 2^+ levels are in the reverse order, the energy levels up to 2.5 MeV can be accounted for. The calculated spectrum shows an obvious tendency that the states of $J=2$ are lower than the observed states. This is attributed to the effect of the adopted two-body matrix elements which were determined by fitting the calculated states of 2^+ and 0^+ well with those states of the experimental levels in copper isotopes"). For the excited states at higher than 2.5 MeV, the states of first 1^+ and second 4^+ observed respectively at 3.188-and 2.794 MeV, as compared with 3.441-and 2.806 MeV from the calculation, the agreement is quite good. As the calculation shows a 3^+ state at 3.775 MeV and a 5^+ state at as higher as 5.712 MeV, it is not surprising that the states of 3^+ and 5^+ were not observed in our experiment. There appear also some states of 2^+ and 4^+ between 3-and 4 MeV in the calculated spectrum. This suggests that it is possible to observe these states experimentally in the region above 4 MeV excitation. In general, the present shell-model calculation seems to give a satisfactory comparison with the experimental results. It is believed that if a full space of the model is used in calculation, the agreement would be improved greatly.

V. CONCLUSION

In this experimental investigation, the energy of the level in ^{64}Zn was accurately determined within the errors of ± 2 keV. We have established a level scheme for ^{64}Zn and suggested the spins-parities of the levels at 3900, 3874, 3602, 3549, 3458, 3300, 3263, 3206, 3092, 3004, 2794 and 2736 keV. The spin-parity of the resonance of de-excitation at $E_{ex}=9772$ keV is more likely to be 2^+, the angular distribution measurement, however, is needed for confirmation. For the shell-model calculation, the satisfactory agreement with experimental results indicates that the low-seniority restriction in the calculation is a useful approximation to reduces the dimensionality for the ^{64}Zn nucleus which has eight valence nucleons outside the ^{56}Ni core.

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