Low-lying levels in Cu and Zn isotopes

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The low-lying levels of Cu and Zn isotopes were excited with 2.0–4.5 MeV proton beam. The deexcited γ rays from these levels were detected and identified in the singles spectra recorded with a 57 c.c. Ge(Li) detector. The safe energies for Coulomb excitation process with protons for these nuclei have been determined from the relative contributions of compound nucleus formation and Coulomb excitation cross sections. The reliable values of transition probabilities for the low-lying levels have also been measured by Coulomb excitation technique using safe bombarding energies. The present results have been compared with the reported measurements and various nuclear model calculations. [S0556-2813(98)02110-4]

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I. INTRODUCTION

The low-lying states in Cu and Zn nuclei have been the subject of several theoretical and experimental investigations. The ^{63}Cu nucleus has been studied via radioactive decay [1,2], nuclear reactions [3–7], and the Coulomb excitation technique [8–10]. The Coulomb excitation results of Kulkarni and Navalkele [10] for low-lying levels up to 1861 keV in ^{63}Cu with 3.25–4.25 MeV protons seem to be fortuitous as Krivonosov *et al.* [11] have observed that the compound nucleus contribution to the differential cross sections for the first excited level at 670 keV dominates over Coulomb excitation with $E_p > 2.7$ MeV.

For ^{67}Zn, the nuclear structure data up to 1991 have been summarized in Nuclear Data Sheets [12]. Information on low-lying levels have been obtained via radioactive decay [13], nuclear reactions [14–17], and Coulomb excitation [18,19]. However, the ambiguity about the existence of a 871 keV level and disagreement of $B(E2)$ values with theoretical calculations could not be resolved. Also the ^{65}Cu and even A nuclei of Zn have not been investigated by proton Coulomb excitation. In view of the above reasons, it was thought to reinvestigate these nuclei and to establish the reaction mechanism with 2.0–4.5 MeV protons and to find the reliable values of transition probabilities. This work has been a part of our systematic Coulomb excitation studies of low-Z nuclei with protons [20].

II. REACTION MECHANISM

The accurate and more reliable spectroscopic information can be extracted only from the knowledge of the reaction mechanism. For the inelastic scattering of low-energy protons, the total cross section may be described as the sum of the direct reaction, compound nuclear reaction, and Coulomb excitation cross sections. The direct reaction contribution is unimportant for the protons of $E_p < 5$ MeV [11]. The reported empirical relation for the safe energy [21] for Coulomb excitation of a nucleus is applicable only for the heavy projectiles. In the present investigation, the reaction mechanism has been ascertained by comparison of the experimental results with detailed theoretical calculations of compound nucleus formation and Coulomb excitation for the given range of proton energies. The calculations for the compound nucleus contribution were made with a computer code CINDY [22]. All the possible channels through $(p,p'\gamma)$, $(p,n\gamma)$, $(p,\alpha\gamma)$, and (p,γ) reactions were assumed to be competing channels. The optical potential parameters used in these calculations are derived by Perey [23], Wilmore and Hodgson [24], and Perey and Perey [25] for proton, neutron, and α's, respectively. The level density relation chosen for this procedure was that of Gilbert and Cameron [26].

III. EXPERIMENTAL PROCEDURE AND DATA ANALYSIS

The experiment was performed using proton beam from the Variable Energy Cyclotron at Panjab University, Chandigarh. The self-supporting natural metallic foils of Cu and Zn with 99.9% purity were used as targets. Each target was positioned at 45° to the beam axis and the deexcited γ rays were detected by a shielded 57 c.c. Ge(Li) detector having a resolution of 1.9 keV for the 1332 keV γ ray of ^{60}Co. The detector was placed at 55° with respect to the beam direction to avoid anisotropic effects. Since the target was sufficiently thick to absorb all the incident protons, it worked as a Faraday cup for the charge collection. The singles spectra were taken at different proton energies (2.0–4.5 MeV). The details of the experiment are given in our previous publications [20,27].

A typical γ-ray spectrum with 3.3 MeV proton beam on copper target has been shown in Fig. 1. The origin of the observed γ rays was assigned by taking into account the background spectrum with the machine on. From the observed spectra at various incident proton energies, the branching ratios were obtained. The thick target yields per incident proton for the excited levels corresponding to the compound nucleus and Coulomb excitation process were obtained. The cross section corresponding to the compound nucleus formation was calculated with the code CINDY. Using the various contributions, the thick target yields per in-

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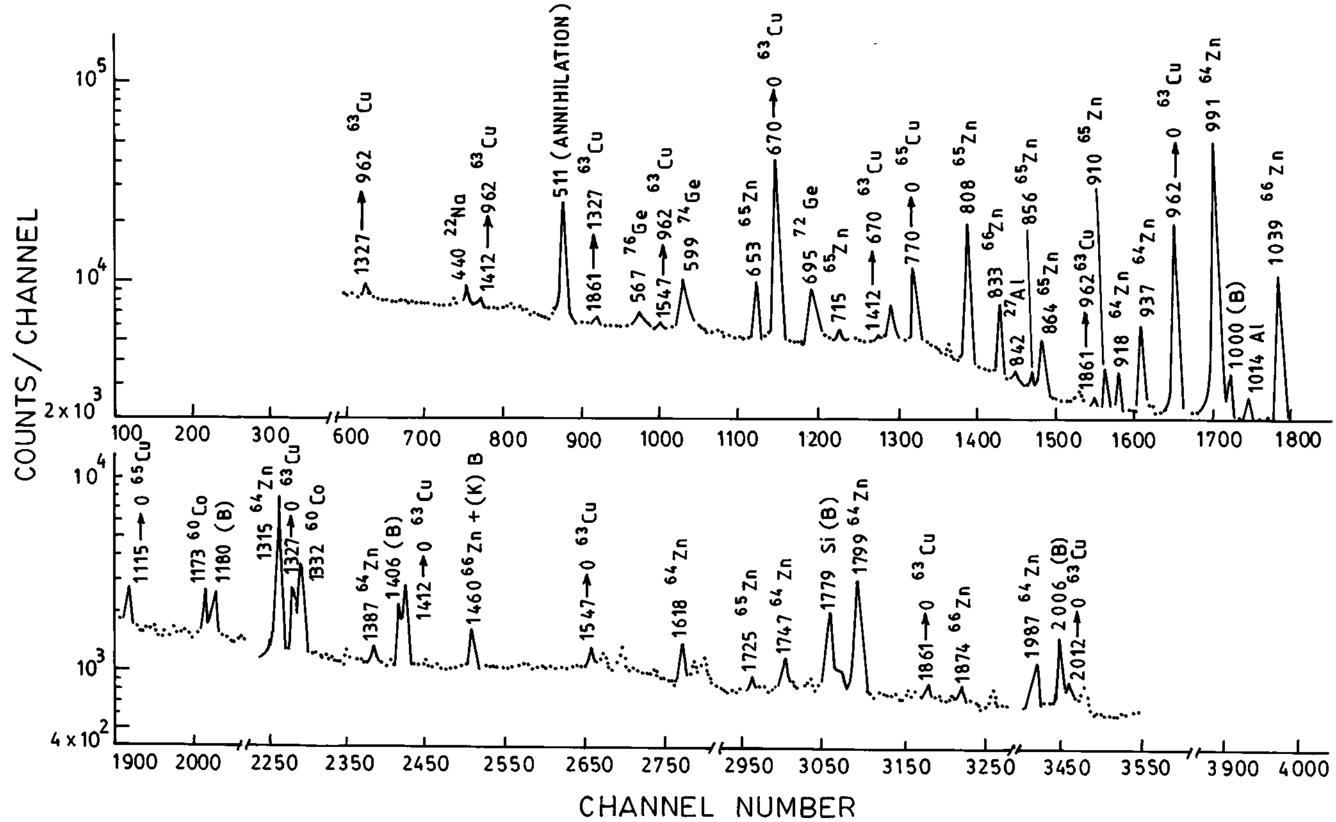

FIG. 1. A typical γ-ray spectrum from Cu+p reaction at E_p=3.3 MeV taken at 55° with respect to the beam direction.

cident proton for the excited levels were measured and compared with the theoretical yields corresponding to the compound nucleus formation as well as the Coulomb excitation process [28]. From this comparison, the safe energy for the Coulomb excitation process was obtained for each nucleus keeping in mind the compound contribution to the total yield <5%. The net yield for Coulomb excitation was obtained by the subtraction of the compound nucleus thick target yield from the experimental yield. Since the direct reaction contribution was negligible for the experimental range of proton energies, this net yield was only due to the Coulomb excitation mechanism. The reduced transition

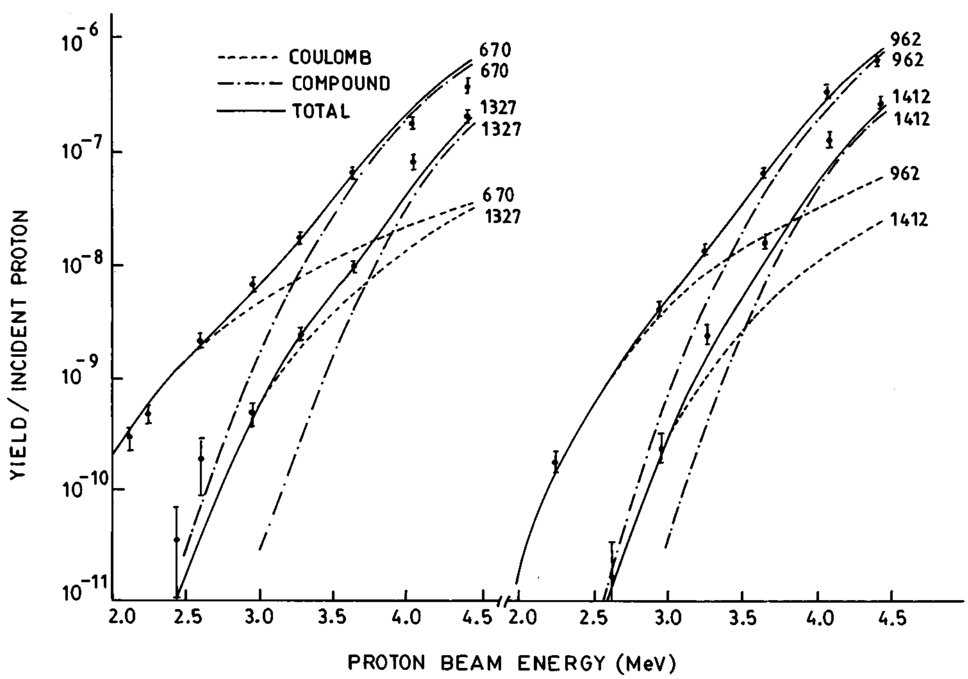

FIG. 2. Excitation functions for the low-lying levels of ^{63}Cu.

TABLE I. Branching ratios and the $B(E2)$ values along with their comparison with previous results for levels of ^{63}Cu.

Level (keV)	γ ray (keV)	Branching ratios	$B(E2)$ e^2 cm$^4\times10^{-50}$ Present	Ref. [9]	Ref. [10]	Ref. [29]	Ref. [39]
669.8	669.8	100	1.20±0.06	1.15±0.15	1.13±0.08	1.19±0.08	1.21
962.2	962.2	100	3.60±0.17	3.15±0.44	3.43±0.24	3.61±0.33	3.57
1327.1	1327.1	83.2±0.8	4.5±0.4	4.40±0.26	4.06±0.30	5.7±0.5	3.56
	365.0	16.8±0.5					
1412.1	1412.1	76.8±0.1	0.86±0.24	0.27±0.06	1.64±0.12		0.03
	742.2	4.5±0.8					
	449.9	18.7±0.8					
1547.1	1547.1	78.0±1.15					
	877.2	1.5±0.8					
	584.9	20.5±1.0					
1861.3	1861.1	55.3±1.2					
	899.1	41.2±1.0					
	534.2	3.5±1.0					
2012.3	2012.3	55					
	1342.5	14					
	1050.1	31					

probabilities for low-lying states were measured by comparing the net Coulomb yield with the theoretical yield based on the Coulomb excitation theory of Alder *et al.* [28] The method of analysis has been described in detail in our previous work [20,27].

IV. RESULTS AND DISCUSSION

A. The nucleus ^{63}Cu

The theoretical Coulomb excitation and compound nucleus formation yields along with the total experimental yield are plotted together as shown in Fig. 2. From this comparison, the safe energy for the Coulomb excitation mechanism in ^{63}Cu is found to be 2.6 MeV for the 670 keV state. It increases slowly with the level energy and becomes 3.0 MeV for the 412 keV state. The higher excited states at 1547, 1861, and 2012 keV were found to have negligible yields up to 3.0 MeV proton energy and follow the compound nucleus thick target yields above 3.5 MeV. Thus the $B(E2)$ values are measured only for the levels at 670, 962, 1327, and 1412 keV. The values for the first two levels are found in excellent agreement with the reported measurements through DSAM [9]. The $B(E2)$ values for the higher levels up to 1861 keV by Kulkarni and Navalkele [10] seem to be erroneous and fortuitous as their measurements were based on the wrong assumption of Coulomb excitation mechanism with 3.25–4.25 MeV proton beams. In the present results the contribution of compound nucleus formation has been taken into account. The branching ratios obtained in this work are also in excellent agreement with the values reported by Papadopoules [9]. The branching ratios and the comparison of our $B(E2)$ values with the previous results [9,10,29] are given in Table I.

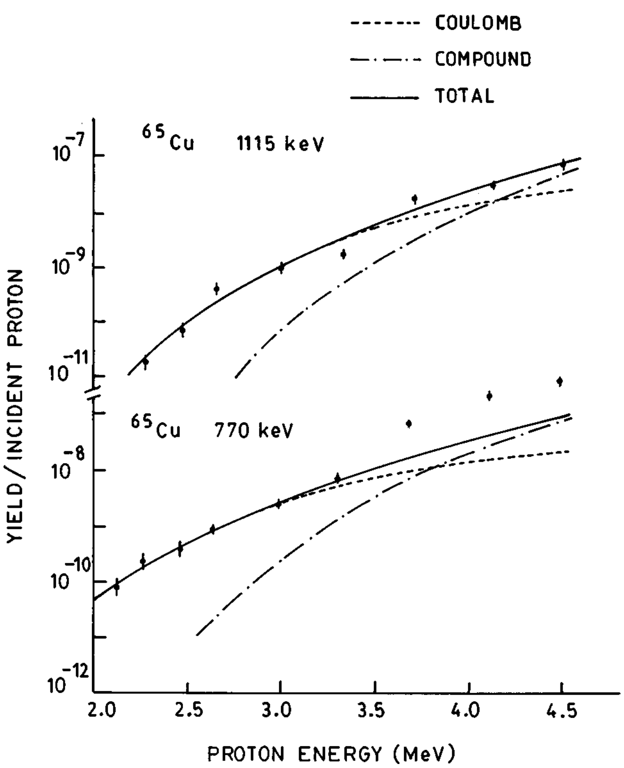

FIG. 3. Excitation functions for the low-lying levels of ^{65}Cu.

B. The nucleus ^{65}Cu

Only the first two levels of ^{65}Cu at 770 and 1115 keV energies were studied in this work as the excitation of the third level and other higher levels is very small with $E_p < 3.0$ MeV proton beam. The excitation functions in Fig. 3

TABLE II. The $B(E2)$ values along with their comparison with previous results for the levels of ^{65}Cu.

Level (keV)	Measured Values of $B(E2)$ e^2 cm$^4\times10^{-50}$ Present	Ref. [30]	Ref. [31]	Ref. [32]	Ref. [33]
770	1.00±0.05	1.02±0.11	1.0	0.87	
1115	3.06±0.21	3.45±0.38	2.8	2.7	2.8±0.4

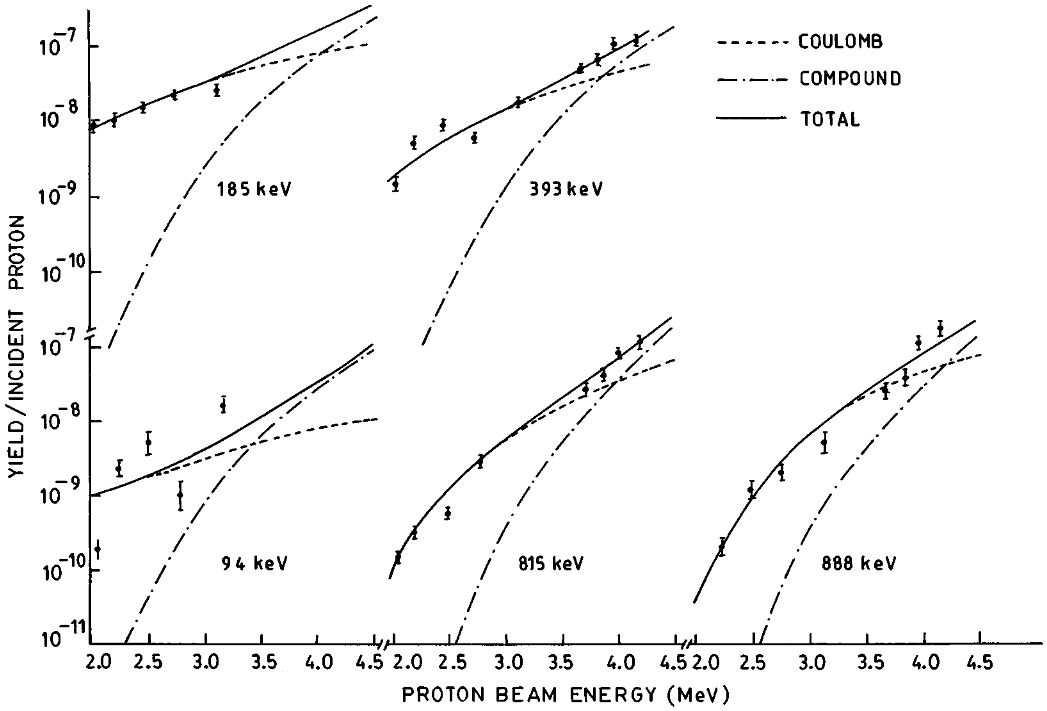

FIG. 4. Excitation functions for the low-lying levels of ^{67}Zn.

show that the safe energies for the 770 and 1115 keV levels are 2.8 and 3.0 MeV, respectively. The reduced transition probabilities for these levels were measured at $E_p < 3.0$ MeV and found to be in excellent agreement (Table II) with previously measured values [30–33].

C. The nucleus ^{67}Zn

The excitation functions for the low-lying levels were measured at various incident proton energies and compared with the theoretical values of Coulomb and compound nucleus formation yields. Figure 4 shows the comparison of experimental and theoretical yields for ^{67}Zn. The safe energy for Coulomb excitation below 1 MeV excitation is found to be 2.9 MeV. The $B(E2)$ values for the low-lying levels were obtained after subtracting the contribution of compound nucleus formation and the feeding from upper levels. The $B(E2)$ values for the levels at 184.4, 814.6, and 888.2 keV are in good agreement with the previous measurements [18,19] and the theoretical calculations [34–36]. But the $B(E2)$ values for the 93 and 393 keV levels differ from previous experimental results as well as with the theory as shown in Table III. Similar to the previous studies [14–16,19], we were also unable to excite a level at 871 keV as observed by Throop *et al.* [18] in the Coulomb excitation measurements.

TABLE III. Branching ratios and the $B(E2)$ values along with their comparison with previous results for the levels of ^{67}Zn.

Level	E_γ	I_γ	Experimental $B(E2)$ e^2 cm$^4\times10^{-50}$			Theoretical $B(E2)$ e^2 cm$^4\times10^{-50}$		
(keV)	(keV)	(%)	Present	Ref. [19]	Ref. [18]	Ref. [34]	Ref. [35]	Ref. [36]
93.1	93.1	100	0.18 ± 0.07			0.16	0.03	0.12
184.4	184.4	85	1.92 ± 0.10	1.9 ± 0.2	1.90 ± 0.14	1.84	0.50	1.75
	91.3	15						
393.5	393.5	17.6	1.40 ± 0.40	0.078 ± 0.015	0.049 ± 0.003	<0.01	0.98	0.00
	300	65.4						
	209	17.1						
814.6	814.6	90.4	2.85 ± 0.20	2.7 ± 0.5	2.9 ± 0.2	3.31	2.93	3.09
	630	9.5						
	421	<1						
888.2	888.2	50.3	0.88 ± 0.06	0.80 ± 0.16	0.86 ± 0.06	0.70	0.98	0.65
	795	20.4						
	704	5.1						
	495	24.2						

TABLE IV. The $B(E2)$ values along with their comparison with previous results for the first levels of ^{64,66,68,70}Zn.

Isotope	Level (keV)	Measured Values of $B(E2)$ e^2 cm^4$\times 10^{-50}$ Present	Ref. [18]	Ref. [37]	Ref. [38]
^{64}Zn	992	11.2±0.6	16.1±1.2	15.5±0.9	17.0±1.5
^{66}Zn	1039	13.5±0.8	15.4±1.3	13.7±1.0	14.5±1.3
^{68}Zn	1077	10.5±0.7		11.1±0.8	12.5±1.6
^{70}Zn	884	23.5±2.5		20.5±1.9	16.0±1.9

D. The nuclei ^{64,66,68,70}Zn

The compound nucleus contributions have been subtracted from the experimental thick-target yields and the $B(E2)$ values were obtained for the first excited states of these nuclei. The $B(E2)$ values for the ^{64,66,68}Zn nuclei are in good agreement with the literature. The error in the $B(E2)$ value for the ^{70}Zn nucleus is more due to small natural abundance (0.62%). The present results on reduced transition probabilities along with previous values [18,37,38] are given in Table IV.

V. CONCLUSION

The present work provides the safe projectile energy for Coulomb excitation with proton beam for the low-lying levels of ^{63,65}Cu and Zn isotopes. The higher value of safe energy for ^{65}Cu may be understood on the basis of the smaller Q value for the $(p,n\gamma)$ reaction for ^{65}Cu compared to ^{63}Cu. Hence the competition between $(p,p'\gamma)$ and (p,γ) is more favorable for ^{63}Cu. Our $B(E2)$ values for the first three levels of the ^{63}Cu nucleus support the particle-phonon interaction model used by de Jager and Boeker [39] using the shell model configuration of an extra proton in free valance space. The present $B(E2)$ measurement for the 93 keV level of ^{67}Zn is best explained by the Alaga model used by Vanen Berghe [34]. The calculations of Allaart *et al.* [36] for $B(E2)$ values through quasiparticle-cluster vibration model (QCVM) are found as a whole in excellent agreement with our experimental results for ^{67}Zn. The relatively high value for 393 keV is in reasonable agreement with the shell model calculations [35]. The $B(E2)$ values for the first excited states of the even isotopes of zinc are also found in close agreement with the shell model calculations of Heinen *et al.* [35] with active particle distributed in the $2p_{3/2}$, $1f_{5/2}$, and $2p_{1/2}$ orbits outside a closed ^{56}Ni core.

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