PHYSICAL REVIEW VOLUME 112, NUMBER 3 NOVEMBER 1, 1958

Excited States of Cu^{64} and Cu^{66}†

R. P. DE FIGUEIREDO,* M. MAZARI,‡ AND W. W. BUECHNER
Physics Department and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received July 14, 1958)

The $Cu^{63}(d,p)Cu^{64}$ and $Cu^{65}(d,p)Cu^{66}$ reactions have been investigated through studies of the proton groups arising from the deuteron bombardment of thin targets of isotopically enriched copper. The incident deuteron beam, with energies ranging from 6.00 to 6.55 Mev, was obtained from an electrostatic accelerator, and the protons were analyzed with a high-resolution magnetic spectrograph. In the region of excitation up to 3.80 Mev, sixty-five excited states in Cu^{64} and fifty-five in Cu^{66} have been measured. The Q values for the transitions to the ground states of Cu^{64} and Cu^{66} are 5.691±0.008 Mev and 4.832±0.008 Mev, respectively.

IN a continuation of our previous studies on the copper isotopes,[1] we have investigated the $Cu^{63}(d,p)Cu^{64}$ and $Cu^{65}(d,p)Cu^{66}$ reactions. In the present experiments, thin targets containing copper enriched, respectively, in the isotopes Cu^{63} and Cu^{65} were bombarded by deuterons from the MIT-ONR accelerator, and the resulting proton groups were analyzed with the broad-range magnetic spectrograph. The targets were prepared by vacuum evaporation of the isotopically enriched copper metal onto thin Formvar films. The degree of enrichment in the Cu^{63} and Cu^{65} isotopes was 99.4% and 98.2%, respectively. (The enriched isotopes were obtained from the Stable Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.)

For each reaction, four exposures were made at angles of observation of 20, 30, 45, and 90 degrees and at incident deuteron beam energies ranging from 6.00 to 6.55 Mev. The spectrograph field was adjusted so that the ground-state groups would appear near the high-energy end of the plates. For this purpose, the expected energies of the groups associated with the ground-state transitions were calculated from the data of Bartholomew and Kinsey[2] on the gamma rays originating from slow neutron capture in natural copper. In these calculations, the assumption was made that the 7.91- and 7.01-Mev gamma rays corresponded to transitions directly to the ground states of Cu^{64} and Cu^{66}, respectively. In one of the exposures with each target, the spectrograph field was sufficiently high so that protons having energies up to 1.1 Mev higher than those of the expected ground-state groups would have been recorded.

Two long exposures were made at an angle of 90 degrees to search for alpha-particle groups from the $Cu^{63}(d,\alpha)Ni^{61}$ and the $Cu^{65}(d,\alpha)Ni^{63}$ reactions. For these exposures, the field in the spectrograph was raised to a high value consistent with the expected Q values for these reactions. Several alpha-particle groups were detected, but their intensities were too low to permit an identification of their origin.

Figure 1 shows a typical proton spectrum from the $Cu^{63}(d,p)Cu^{64}$ reaction. The data for this figure were obtained at an angle of 45 degrees with an incident beam energy of 6.09 Mev. A similar spectrum from the $Cu^{65}(d,p)Cu^{66}$ reaction at an angle of 30 degrees and an incident beam energy of 6.55 Mev is shown in Fig. 2. In each figure, the proton groups arising from (d,p) reactions with the nuclei of the impurities present in the targets are denoted by the chemical symbols of the associated residual nuclei. These groups were identified by a consideration of their respective Q values calculated on the basis of the assumed impurities and by a study of their characteristic shift in position with respect to the remaining peaks of the spectrum as the angle of observation was varied. The proton groups associated with the energy levels in the copper isotopes are labeled by numbers in order of increasing excitation energy.

Excluding those which originated from the contaminants, the highest energy proton group was attributed to the transition leading to the ground state of the residual copper nucleus. On this basis, the ground-state Q values for the $Cu^{63}(d,p)Cu^{64}$ and the $Cu^{65}(d,p)Cu^{66}$ reactions were determined as 5.691±0.008 Mev and 4.832±0.008 Mev, respectively. As is indicated by the data of Figs. 1 and 2, the density of states in both Cu^{64} and Cu^{66} is quite high, and the Q values for the states lying higher in excitation than 3.80 Mev were not calculated. A detailed study of the states above this energy would have required thinner targets and higher resolution of both the beam analyzing and the spectrograph magnet than was employed in the present experiments. The data indicate that, in the region of excitation between 3.80 and 6.20 Mev in Cu^{64}, there are approximately sixty-five excited states, and in Cu^{66} there are approximately sixty excited states between 3.80 and 6.00 Mev.

In the regions between the ground states and 3.80 Mev, the positions of sixty-five excited states in Cu^{64} and fifty-five states in Cu^{66} were determined. These

† This work has been supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
* Supported by Junta de Investigações do Ultramar, Lisbon, Portugal.
‡ Now at the National University of Mexico.
[1] Mazari, Buechner, and de Figueiredo, Phys. Rev. **108**, 373 (1957).
[2] G. A. Bartholomew and B. B. Kinsey, Phys. Rev. **89**, 386 (1953).

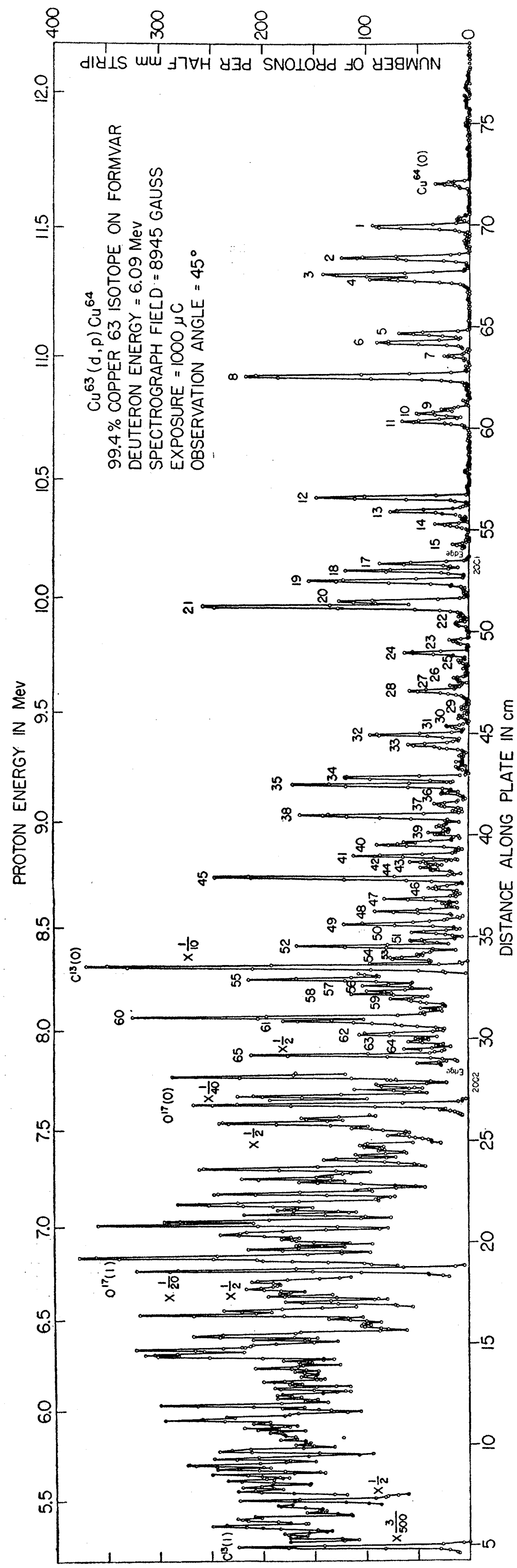

Fig. 1. Typical proton spectrum from the $Cu^{63}(d,p)Cu^{64}$ reaction; incident beam energy = 6.09 Mev.

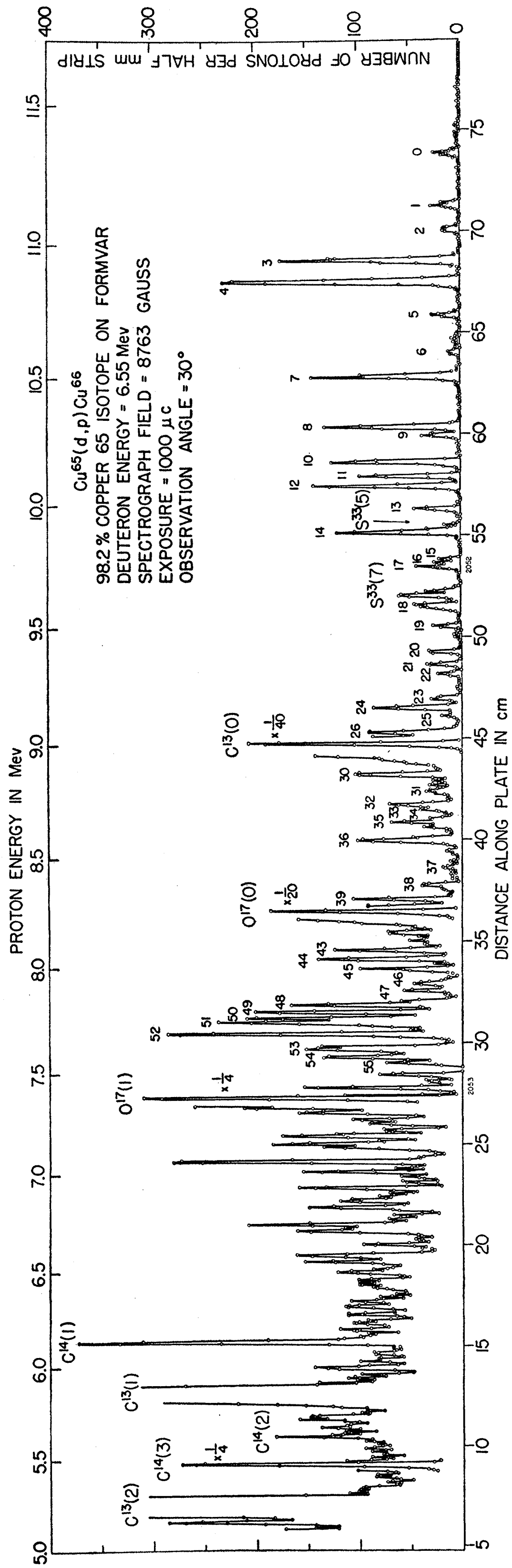

Fig. 2. Typical proton spectrum from the $Cu^{65}(d,p)Cu^{66}$ reaction; incident beam energy = 6.55 Mev.

results are tabulated in Tables I and II and are summarized in the energy-level diagrams in Fig. 3. The values listed represent the average of those computed from the different exposures. As in the previous work,[1] all the estimated errors are at least twice as large as the deviations of the individual measurements from the average values listed. In Table I, the results were calculated from all the four exposures on the Cu^{63} target. The group associated with the sixteenth state

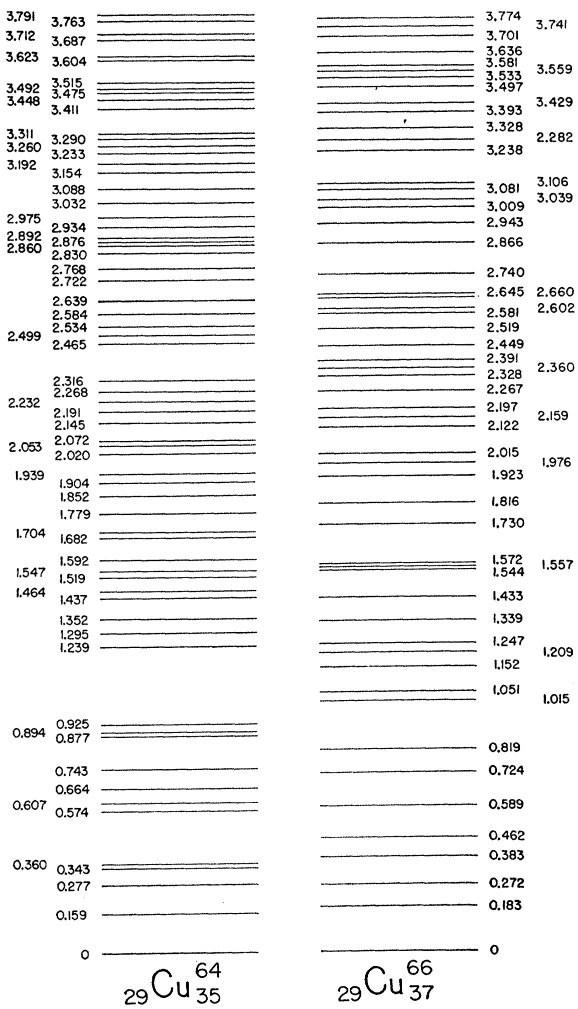

FIG. 3. Energy-level diagram of Cu^{64} and Cu^{66} levels.

in Cu^{64} is not visible in Fig. 1, since it occurred in the region between two of the photographic plates. This group was observed, however, in all the other exposures. In the case of the results listed in Table II, the energy values for the first ten levels were determined from the four exposures on the Cu^{65} target. Of the others, the values for levels 11 through 14 were obtained from the data taken at 20, 30, and 45 degrees, while the remaining levels were determined from the 30- and 45-degree exposures. In the case of the Cu^{65} target, the 20-

TABLE I. Excited states of Cu^{64} as determined from the $Cu^{63}(d,p)Cu^{64}$ reaction ($Q_0=5.691\pm0.008$ Mev).

Level	Excitation energy (Mev)	Level	Excitation energy (Mev)
1	0.159±0.008	34	2.465±0.008
2	0.277±0.008	35	2.499±0.008
3	0.343±0.008	36	2.534±0.008
4	0.360±0.008	37	2.584±0.008
5	0.574±0.008	38	2.639±0.008
6	0.607±0.008	39	2.722±0.008
7	0.664±0.008	40	2.768±0.008
8	0.743±0.008	41	2.830±0.008
9	0.877±0.008	42	2.860±0.008
10	0.894±0.008	43	2.876±0.008
11	0.925±0.008	44	2.892±0.008
12	1.239±0.008	45	2.934±0.008
13	1.295±0.008	46	2.975±0.008
14	1.352±0.008	47	3.032±0.008
15	1.437±0.010	48	3.088±0.008
16	1.464±0.008	49	3.154±0.010
17	1.519±0.008	50	3.192±0.010
18	1.547±0.008	51	3.233±0.010
19	1.592±0.008	52	3.260±0.010
20	1.682±0.008	53	3.290±0.010
21	1.704±0.008	54	3.311±0.010
22	1.779±0.008	55	3.411±0.020
23	1.852±0.008	56	3.448±0.010
24	1.904±0.008	57	3.475±0.010
25	1.939±0.008	58	3.492±0.010
26	2.020±0.008	59	3.515±0.010
27	2.053±0.008	60	3.604±0.010
28	2.072±0.008	61	3.623±0.010
29	2.145±0.008	62	3.687±0.010
30	2.191±0.010	63	3.712±0.010
31	2.232±0.008	64	3.763±0.010
32	2.268±0.008	65	3.791±0.010
33	2.316±0.008		

TABLE II. Excited states of Cu^{66} as determined from the $Cu^{65}(d,p)Cu^{66}$ reaction ($Q_0=4.832\pm0.008$ Mev).

Level	Excitation energy (Mev)	Level	Excitation energy (Mev)
1	0.183±0.008	(29)[a]	2.391±0.008
2	0.272±0.008	30	2.449±0.008
3	0.383±0.008	(31)	2.519±0.008
4	0.462±0.008	32	2.581±0.008
5	0.589±0.008	33	2.602±0.008
6	0.724±0.010	34	2.645±0.008
7	0.819±0.008	35	2.660±0.008
8	1.015±0.008	36	2.740±0.008
9	1.051±0.010	37	2.866±0.008
10	1.152±0.008	38	2.943±0.008
11	1.209±0.008	39	3.009±0.008
12	1.247±0.008	(40)	3.039±0.008
13	1.339±0.008	(41)	3.081±0.008
14	1.433±0.008	(42)	3.106±0.008
15	1.544±0.008	43	3.238±0.008
16	1.557±0.008	44	3.282±0.008
17	1.572±0.008	45	3.328±0.008
18	1.730±0.008	46	3.393±0.008
19	1.816±0.008	47	3.429±0.008
20	1.923±0.008	48	3.497±0.008
21	1.976±0.008	49	3.533±0.008
22	2.015±0.008	50	3.559±0.008
23	2.122±0.008	51	3.581±0.008
24	2.159±0.008	52	3.636±0.008
25	2.197±0.008	53	3.701±0.008
26	2.267±0.008	54	3.741±0.012
(27)	2.328±0.008	55	3.774±0.012
(28)	2.360±0.008		

[a] The excitation energy values for levels enclosed in parentheses were obtained from only one exposure.

degree exposure was low (639 microcoulombs), thus giving rise to a poor yield of protons for the levels higher than the fourteenth. In the case of the 90-degree exposure, only the proton groups associated with the ground state and with the first ten excited states in Cu^{66} were used for the energy determinations. In Table II, the values for levels numbered (27), (28), (29), (40), (41), (42), and (31) were obtained from only one exposure and these numbers are therefore enclosed in parentheses. Groups from impurities in the targets obscured the first six of these groups in the 30-degree exposure, as shown in Fig. 2, and the group associated with the thirty-first level was obscured in the exposure at 45 degrees.

Of the previous work[3] on Cu^{64} and Cu^{66}, that most relevant to the present work is that of Bartholomew and Kinsey[2] on the neutron capture gamma rays from natural copper. From their highest energy gamma ray, 7.914 Mev, a predicted Q value for the corresponding (d,p) reaction is 5.688 Mev. This is in excellent agreement with the value of 5.691 Mev measured in the present work. This Q value may also be calculated from the measured masses[4] of Cu^{63} and Zn^{64} and the Cu^{64} beta-decay energy.[3] This calculation leads to a Q value of 5.690 Mev. None of the other capture gamma rays reported have the energy which, on the basis of the present measurement of the $Cu^{65}(d,p)Cu^{66}$ Q value, would correspond to a ground-state transition following slow neutron capture in Cu^{65}. The measured Q value, 4.832 Mev, is in good agreement, however, with the value of 4.82 Mev calculated from the masses[4] of Cu^{65} and Zn^{66} and the beta-decay energy of Cu^{66}.

It has been suggested[2,4] that the 7.01-Mev gamma ray was associated with neutron capture in Cu^{65}. The present results indicate that this gamma ray originates from capture in Cu^{63} and is associated with a transition to the 0.894-Mev level in Cu^{64}. All of the other capture gamma rays can be fitted, within the experimental errors, into the level scheme of Cu^{64} shown in Fig. 3. However, the 6.69-, 6.05-, 5.75-, 5.64-, 5.31-, and 5.07-Mev gamma rays can equally as well be fitted into the Cu^{66} level diagram.

ACKNOWLEDGMENTS

We wish to acknowledge the assistance of our plate-reading group, and particularly of Mr. Wilton Tripp, in this investigation.

[3] *Nuclear Level Schemes*, $A=40-A=92$, compiled by Way, King, McGinnis, and van Lieshout, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

[4] Quisenberry, Scolman, and Nier, Phys. Rev. **104**, 461 (1956).