Study of the $Cu^{65}(p,n)Zn^{65*}$ Reaction by Conversion Electrons*

E. M. BERNSTEIN AND H. W. LEWIS
Department of Physics, Duke University, Durham, North Carolina

(Received April 24, 1957)

A magnetic beta-ray spectrometer has been used to study the prompt internal-conversion electrons from low-lying states of Zn^{65} excited by the $Cu^{65}(p,n)Zn^{65*}$ reaction. The data show that there are levels in Zn^{65} at 54±2, 119±2, and 209±3 kev, all levels being excited directly by the p-n reaction. The threshold for exciting the 54-kev level is (2223_{-3}^{+2}) kev, yielding a Q value of $-(2189_{-3}^{+2})$ kev for the reaction to this level. Neutron branching ratios were calculated from the relative yields of conversion electrons. At a bombarding energy of 3.75 Mev the ratios are 1:8:4 for the neutrons leading to the 54-, 119-, and 209-kev levels, respectively.

INTRODUCTION

NUCLEAR reactions which lead to low-energy transitions in the residual nucleus can be studied in some cases by the measurement of the spectrum of prompt internal-conversion electrons with a beta-ray spectrometer. One can observe transitions in which the gamma rays are obscured by background; the resolving power is much better than that obtained with a scintillation gamma-ray detector; and from the conversion ratios for the various atomic shells one can assign multipolarities to the transitions. This technique has been used previously to study nuclear levels excited by Coulomb excitation.[1–4] Using an experimental arrangement similar to the one employed in the Coulomb excitation experiments, we have studied the low-lying levels in Zn^{65} excited by the $Cu^{65}(p,n)Zn^{65*}$ reaction.

From the positron decay of Ga^{65}, transitions of 52, 92, and 114 kev have been assigned[5] to Zn^{65}. This information was used by Marion and Chapman[6] who searched for neutron groups from the $Cu^{65}(p,n)Zn^{65}$ reaction corresponding to levels in Zn^{65} at the above energies. By studying the neutron spectrum with a resonant scatterer, they were able to observe two neutron groups, one to the ground state and the other to a level in Zn^{65} at 118 kev. At a bombarding energy of 3 Mev the intensities of the two groups were approximately equal. No other neutron groups were observed. These same workers examined the gamma-ray spectrum up to 250 kev, but they were unable to identify any gamma rays in the presence of the large neutron background. Their results did not rule out the possibility of other low-lying states in Zn^{65}.

A. EXPERIMENTAL ARRANGEMENT AND TARGETS

The wedge-shaped magnetic beta-ray spectrometer was attached to the beam tube of the Duke University 4-Mev Van de Graaff accelerator in such a way that the beam struck the target in the normal source position. The arrangement is described in greater detail elsewhere.[2] The only modification has been to replace the Geiger counter used in the previous experiments by a thin organic scintillator. This reduced the background from neutrons and gamma rays considerably.

Preliminary results[7] were obtained using a thin natural-copper foil for the target. The data reported here were obtained using a thin copper target electroplated onto a thick carbon backing. The second target was enriched to 98% Cu^{65}. Its thickness was less than 35 kev at 3 Mev.

B. ELECTRON SPECTRUM

Figure 1 shows the momentum spectrum obtained at a bombarding energy of 3.75 Mev. The conversion lines are labeled according to the atomic shell and the energy of the transition. The most prominent lines are the K conversion lines from the 54-, 119-, 155-, and 209-kev transitions. The L and M lines for each transition are not resolved and appear as one peak. The K line from the 65-kev transition is not resolved from the 54-kev $L+M$ line. However, the fairly weak 65-kev $L+M$ line does appear alone. A very weak line which corresponds to K conversion from a transition of 90 kev is also indicated in the figure. The existence of this line is quite certain since it was more intense in measurements with a thicker target. The sloping background at low energies is due to "stopping electrons" ejected from the target atoms by the protons in the

TABLE I. Transitions in Zn^{65}.

Energy (kev)	Conversion lines observed	$K/(L+M)$	Multipolarity[a]
54±2	K, $L+M$	6.1	$E2$
65±2	K, $L+M$	7.3	dipole
90±2	K	...	...
119±2	K, $L+M$	8.6	dipole
155±3	K, $L+M$	8.2	dipole
209±3	K, $L+M$	7.4	dipole or quadrupole

[a] See text, Sec. B.

* Supported by the U. S. Atomic Energy Commission.
[1] Huus, Bjerregaard, and Elbek, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 30, No. 17 (1956).
[2] E. M. Bernstein and H. W. Lewis, Phys. Rev. 100, 1345 (1955).
[3] E. M. Bernstein and H. W. Lewis, Phys. Rev. 105, 1524 (1957).
[4] Moore, Class, Prossler, and Schiffer, Bull. Am. Phys. Soc. Ser. II, 1, 88 (1956).
[5] B. Craseman, Phys. Rev. 93, 1034 (1954).
[6] J. B. Marion and R. A. Chapman, Phys. Rev. 101, 283 (1956).
[7] E. M. Bernstein and H. W. Lewis, Bull. Am. Phys. Soc. Ser. II, 2, 61 (1957).

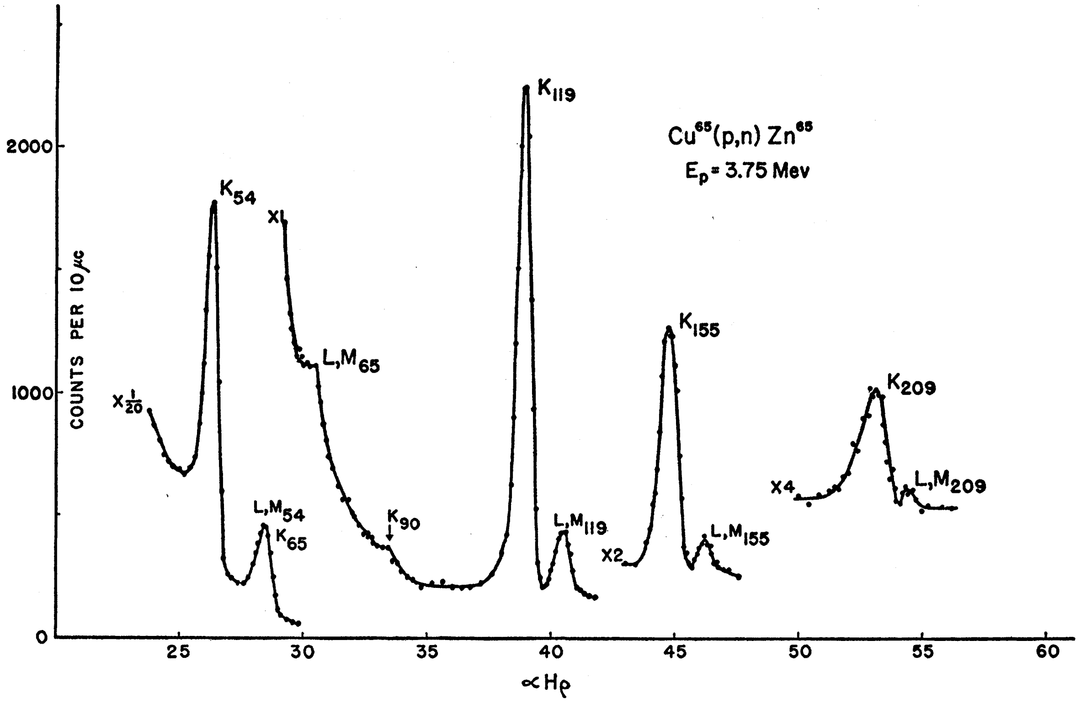

FIG. 1. Momentum spectrum showing the prompt internal-conversion lines following the $Cu^{65}(p,n)Zn^{65*}$ reaction. The bombarding energy is 3.75 Mev. The lines are labeled according to the atomic shell and the energy of the transition. Note the several changes in vertical scale.

stopping process. The rather flat background at higher energies is due mainly to neutrons and gamma rays. With these data one can construct the energy level diagram in Fig. 2. Since all possible transitions between the levels occur, the assignments are unambiguous.

In Table I the transitions observed and the measured $K/(L+M)$ ratios are tabulated. Since the 65-kev transition is a cascade from the 119-kev level, it was possible (see Sec. C) to bombard at such a proton energy that only the 54-kev level was excited. This was necessary in obtaining the $K/(L+M)$ ratio for the 54-kev transition to eliminate the confusion brought about by the presence of the 65-kev K line which is unresolved from the 54-kev $L+M$ line. Unfortunately, except for the 54-kev transition which is $E2$, the $K/(L+M)$ ratios do not lead to unambiguous assignments of the multipolarities. However, they do establish that all the other transitions are dipole except the 209-kev transition which is dipole or quadrupole. If one assumes that all the levels have the same parity, as one might expect from the shell model and from a consideration of Zn^{67} which has a strikingly similar level structure,[8] then in every case except the 209-kev transition the multipolarity is $M1$. The similarity of the two nuclei is supported by the $E2$ nature of the 54-kev transition. The multipolarity of the corre-

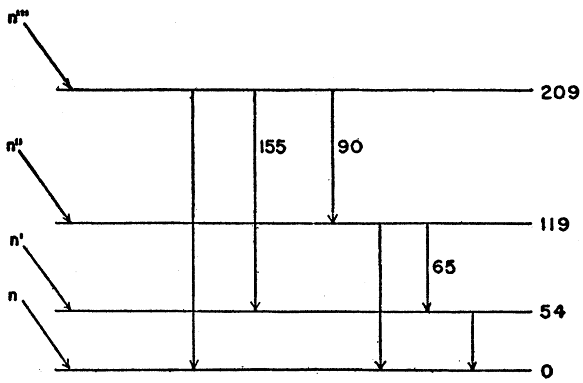

FIG. 2. Energy level diagram for Zn^{65}.

TABLE II. Relative transition probabilities.

Transition (kev)	α_T[b]	Relative number of transitions[a] Conversion electrons	Gamma rays	Total
54	7	1280	180	1460
65	0.22	60	270	330
90	0.1[c]	~2	~16	~18
119	0.032	60	1840	1900
155	0.015	12	833	845
209[d]	0.009 (0.042)	2.5 (2.5)	278 (61)	280 (63)

[a] Arbitrarily normalized. The proton energy is 3.75 Mev.
[b] Total conversion coefficient using multipolarities given in Table I.
[c] Assuming dipole transition.
[d] Two numbers are given since the 209-kev transition can be dipole or quadrupole. The first number is for dipole; the second, in parentheses, is for quadrupole.

[8] *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).

sponding transition from the first excited state to the ground state in Zn^{67} is $E2$ rather than $M1$ which is also allowed. Even with the above assumption the spins of the levels in Zn^{65} are not uniquely determined, but the multipolarities of *all* the transitions are the same as for the corresponding transitions in Zn^{67}, whose levels have spins of (from the ground state up) $5/2^-$, $3/2^-$, $5/2^-$, $3/2^-$.

Even though the electric or magnetic nature of the transitions is not definitely established, one can calculate the gamma ray and total branching ratios from the conversion ratios. This is possible since the conversion coefficients in Zn for the energies involved are the same within a few percent for a given 2^l-pole transition ($l=1$ or 2) whether they are magnetic or electric. The results of these calculations are given in Table II.

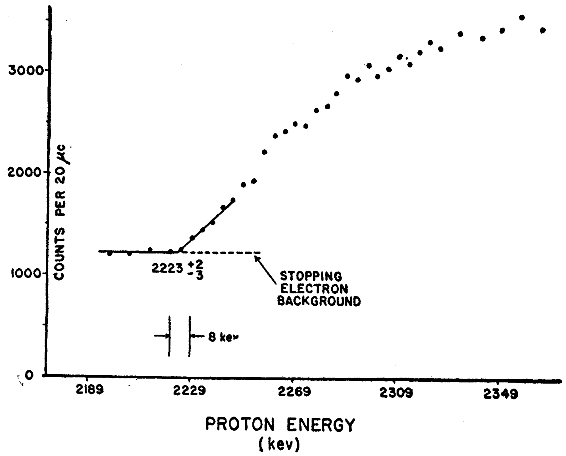

FIG. 3. Excitation function of the 54-kev transition showing the threshold. The background is due to "stopping electrons" (see text Sec. B).

C. THRESHOLDS AND EXCITATION FUNCTIONS

The yield of the K conversion line from the 54-kev transition as a function of proton energy is shown in Fig. 3. The proton energy was determined with a cylindrical electrostatic analyzer set to an energy resolution of 1/1000 and calibrated with the $Li^7(p,n)$ threshold (1881 kev). It is seen that the threshold for exciting the 54-kev transition is well defined. The threshold energy is (2223_{-3}^{+2}) kev. From this one obtains a Q value of $-(2189_{-3}^{+2})$ kev for the reaction which excites the 54-kev transition. When this is compared with the ground-state Q value[9] of -2132 kev, an energy difference of (57_{-3}^{+2}) kev is obtained. This is in good agreement with the 54 ± 2 kev determined from the momentum spectrum for the energy of the first excited state in Zn^{65}. This also shows that neutrons excite this state directly.

An attempt was made to measure the threshold for exciting the 119-kev transition. However, the yield of this transition just above threshold was quite small compared to background. Although an accurate threshold measurement could not be made it was seen that the 119-kev transition was present at a bombarding energy which was too low to excite the next highest level at 209 kev.

The excitation of the 119-kev transition as a function of incident proton energy from 2.80 to 3.9 Mev determined by the electrostatic analyzer is shown in Fig. 4.

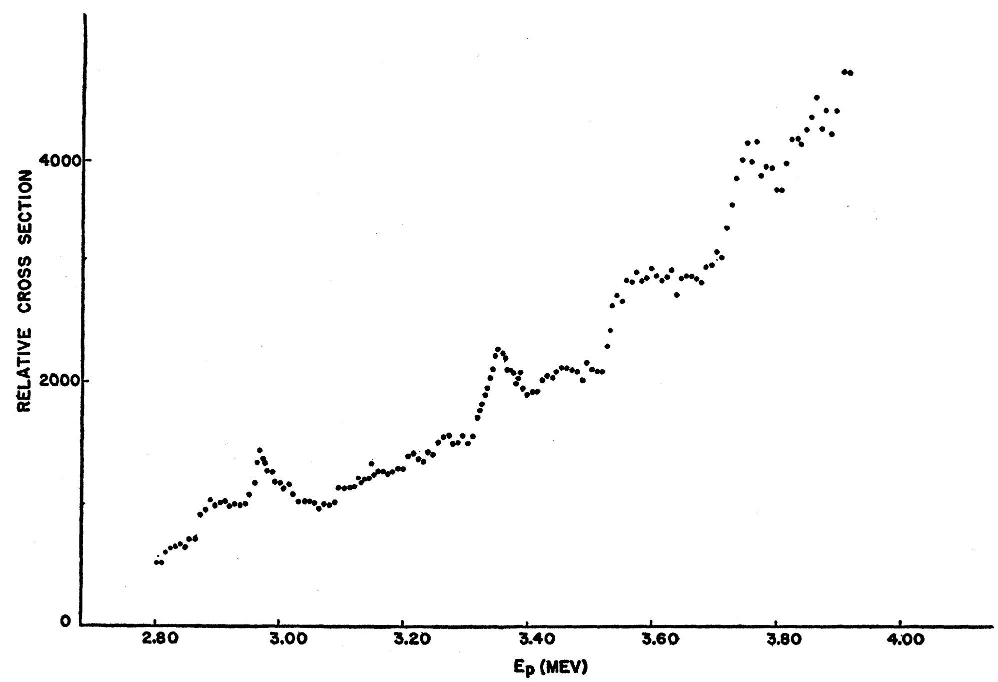

FIG. 4. Excitation of the 119-kev transition as a function of incident proton energy.

[9] J. B. Marion and R. W. Kavanagh, Phys. Rev. 104, 107 (1956).

Since the cascade from the 209-kev level to the 119-kev level is extremely weak, Fig. 4 represents the yield of the neutron group leading to the 119-kev level. The qualitative appearance of this curve, including pronounced resonances, is very similar to the total neutron yield from the $Cu^{65}(p,n)Zn^{65}$ reaction measured[10] with a BF_3 counter.

D. NEUTRON BRANCHING RATIOS

Using the data in Table II, one can calculate the neutron branching ratios to the first three excited states. Sufficient data to do this were taken at three bombarding energies; 3 Mev, 3.75 Mev, and 4 Mev. The results are given in Table III. The experimental uncertainty in the relative intensities is 25%. From the present work nothing can be said about the relative intensity of the neutrons leading to the ground state. However, the previous work[6] at Rice showed that at 3 Mev the groups involving the 119-kev level and the ground state have approximately the same intensity.

[10] Brugger, Bonner, and Marion, Phys. Rev. **100**, 84 (1955).

TABLE III. Branching ratios for the neutron groups.

Level (kev)	Neutron group[a]	Relative intensity[b] 3.00 Mev	3.75 Mev	4.00 Mev
0	n	8[c]	...	...
54	n'	...	1	...
119	n''	8	8	8
209	n'''[d]	3.8 (3.2)	4 (3.5)	3 (2.7)

[a] See Fig. 2.
[b] Arbitrarily normalized to 8 for n'' at each energy.
[c] From reference 5.
[d] See Table II, footnote d.

DISCUSSION

The experiment described illustrates quite nicely the advantages of the rather new technique for studying nuclear reactions. Except for the spins, a rather complete description of the first three excited states of Zn^{65} is obtained. The existence of the level at 54 kev which is directly excited by neutrons severely limits the $Cu^{65}(p,n)Zn^{65}$ reaction as a source of neutrons. This limitation was suggested from the previous neutron work.[6]

PHYSICAL REVIEW VOLUME 107, NUMBER 3 AUGUST 1, 1957

Ionization Following Beta Decay in Krypton-85

ARTHUR H. SNELL AND FRANCES PLEASONTON
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received April 25, 1957)

Following beta decay in the 9.4-year radioactivity of Kr^{85}, the product rubidium atoms are found to be distributed in the following charge spectrum (figures in percent): charge 1, 79.2±1.0; charge 2, 10.9±0.2; charge 3, 3.9±0.1; charge 4, 3.1±0.1; charge 5, 1.51±0.07, charge 6, 0.66±0.04; charge 7, 0.40±0.02; charge 8, 0.19±0.02; charge 9, 0.093±0.01; charge 10, 0.026±0.006; charge 11, unobservable. An interpretation is made in terms of the "shaking off" of extranuclear electrons by the sudden change by +1 in the nuclear charge, the intensity of the charge-2 ions being taken as a direct measure of the probability of "shake-off" from the combined $4s$ and $4p$ shells. The combined intensities of charge 3 and higher are correspondingly equated to the summed probabilities of primary ionizations in the $n=1$, 2, and 3 shells.

THE atomic-charge spectra that result from radioactive decay appear to have a variety and an interest in their own right, reflecting a sensitivity to the nature of the nuclear change that caused the ionization, as well as representing the statistical outcome of the complex atomic rearrangements that follow electron loss from any of the several electron shells of the atom. We have already presented the peaked charge distribution that results from a single internal-conversion event in the 12-day isomer of Xe^{131},[1] and the similarly peaked distribution produced by electron capture in A^{37}.[2] The peaked distributions are caused by vacancy cascades that follow the creation of an electron hole in one of the inner shells. By way of contrast, we wish now to describe a charge spectrum that follows pure beta emission, and we shall see that it consists of a monotonic decrease, sharply falling toward the higher charges. The radionuclide is Kr^{85}, chosen as one in a series that give information uncomplicated by molecular effects.

Although the qualitative comparison of the different kinds of charge spectra is of interest, there is a further significance in the present study, for it provides a new kind of opportunity—and experimentally apparently a good opportunity—for a check of the theory of electron shake-off following an abrupt change in the nuclear charge. It will be recalled that with the rapid escape of the beta particle in a time short compared with the orbital times of the electrons, the change in the nuclear charge from Z to $Z\pm1$ introduces a sudden perturbation into the electrostatic environment of the electrons, with a resulting possibility of excitation or ionization. The process has been considered on a rather general

[1] F. Pleasonton and A. H. Snell, Proc. Roy. Soc (London). (to be published); A. H. Snell and F. Pleasonton, Phys. Rev. **102**, 1419 (1956).
[2] A. H. Snell and F. Pleasonton, Phys. Rev. **100**, 1396 (1955); see also O. Kofoed-Hansen, Kgl. Danske Videnskab. Selskab, Mat-fys. Medd. **29**, 15 (1955), and Phys. Rev. **96**, 1045 (1954).