Properties of Excited States of Pd and Cd Nuclei by Coulomb Excitation

G. M. TEMMER AND N. P. HEYDENBURG
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.
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We have Coulomb-excited the first-excited (2^+) states of most even-even nuclei of Pd and Cd using enriched targets. Three of these states were previously unknown (Pd^{108}, Pd^{110}, and Cd^{116}). We also observed excited states in Pd^{105}, Cd^{111}, and Cd^{113}, the latter yielding a new level at 290 kev. Transition probabilities (lifetimes) for these transitions have been determined and show definite systematic trends.

WE have observed Coulomb excitation of most nuclei of Pd and Cd, using our 6-Mev He^{++} beam[1] and targets enriched in the various isotopes.[2] Because of the $E2$ character of the excitation process, we excite only 2^+ states in the even-even nuclei; a measurement of the energy and yield of gamma radiation emitted from these states amounts therefore to a determination of spin, parity, energy, and transition probability (lifetime) of first-excited states of even-even nuclei. In view of the systematic behavior of the position, spin, and parity of these states,[3,4] it is of interest to obtain information concerning the systematics of their lifetimes as well; no such information for nuclei around $A=100$ is presently available because the lifetimes are beyond the range accessible to fast-coincidence studies (see below).

For the odd-A nuclei the spin assignments are not as definite and the positions of the levels reached are not necessarily equal to the gamma-ray energies observed. For the odd Cd nuclei ($I_0=\frac{1}{2}^+$) the excited states must have $I=3/2^+$ or $5/2^+$; a wider range of possibilities exists for the states excited in $Pd^{105}(I_0=5/2^+)$.

The gamma-ray yields from thick targets of Pd and CdO were measured with a $1\frac{3}{4}$ in.$\times$2 in. NaI(Tl) crystal in our standard arrangement.[5] The He^{++} beam was produced by using a gas stripper similar to the one described by Bittner,[6] but installed some 30 inches below the rf ion source in the accelerating tube. The He^+ ions are stripped of their second electron after having reached about 300 kev, and receive twice the voltage of the remainder of the electrostatic generator. At the present time our knowledge of the energy of the He^{++} beam is somewhat approximate (6.00 ± 0.050 Mev). Up to 0.12 microampere of He^{++} beam has been available. The absolute efficiency of the crystal for the 411-kev gamma radiation from Au^{198} had been determined previously[7]; correction for effective photopeak efficiency at slightly different energies was made adapting the results of some Swiss workers.[8] The enriched CdO yields were converted to equivalent Cd yields by determining the ratio experimentally. (Observed CdO yields had to be multiplied by 1.35.) The thick-target yields were converted to cross sections making some simplifying assumptions suggested by Huus.[9] The cross sections in turn were reduced to transition probabilities $B(E2)$ using the improved theory of Alder and Winther.[10] The justification for the last step rests on empirical[11] and theoretical[10,12] evidence concerning the correctness of the semiclassical treatment of the Coulomb excitation process.*

We shall now discuss the excited levels in some detail.

Palladium.—Figure 1 shows the pulse-height spectra obtained from the even-even isotopes of Pd (with the exception of Pd^{102}, whose enrichment was insufficient). Previously established first-excited states were confirmed with respect to position, spin, and parity in Pd^{104} (550 kev) and Pd^{106} (510 kev); new 2^+ states were found in Pd^{108} (424 kev) and Pd^{110} (370 kev). The latter state is not accessible by other means. The systematic trend in position of these states is very apparent. The heights of the peaks in the pulse-height distributions reflect many factors in addition to transition probability, such as Coulomb excitability, thick-target yield dependence on level energy, and crystal efficiency. When these factors are taken into account, some of the trend remains, as can be seen from Table I. Two lines are observed in Pd^{105} (266 and 433 kev); transition probabilities were computed assuming that these energies correspond to levels at those energies, and that their sole decay occurs via the observed gamma ray.

[1] Some preliminary results on these and other medium-heavy nuclei, using natural targets, were presented at the Glasgow International Conference on Nuclear Physics, July 13–17, 1954, and can be found in the Proceedings (Pergamon Press Ltd., London, 1955).
[2] Obtained on loan from Brookhaven National Laboratory through the kindness of G. Scharff-Goldhaber.
[3] G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).
[4] P. Stähelin and P. Preiswerk, Nuovo cimento **10**, 1219 (1953).
[5] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **94**, 1252 (1954).
[6] J. W. Bittner, Rev. Sci. Instr. **25**, 1058 (1954).
[7] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **95**, 861 (1954).
[8] Maeder, Müller, and Wintersteiger, Helv. Phys. Acta **27**, No. 1, 3 (1954).
[9] See also a forthcoming review article on Coulomb excitation in Revs. Modern Phys. by Alder, Bohr, Huus, Mottelson, Winther, and Zupančič.
[10] K. Alder and A. Winther, Phys. Rev. **96**, 237 (1954).
[11] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **96**, 426 (1954).
[12] G. Breit and P. B. Daitch, Phys. Rev. **96**, 1447 (1954); L. C. Biedenharn and C. M. Class, Phys. Rev. **98**, 691 (1955).
* *Note added in proof.*—We recently examined the thick-target excitation function, from 2.75- to 7.00-Mev alpha energy, for the 370-kev transition in Pd^{110}, and found it to be in very good accord with the $E2$ theory.

These assumptions are completely justified in the case of the even-even nuclei. Internal conversion correction has been neglected in view of the smallness of the conversion coefficients.

Cadmium.—Figure 2 shows the pulse-height spectra obtained from the even-even isotopes of Cd (with the exception of Cd^{106} and Cd^{108}, whose enrichment was insufficient). Previously established first-excited 2^+ states were confirmed in Cd^{110} (654 kev), Cd^{112} (620 kev), and Cd^{114} (550 kev); a new 2^+ state was found in Cd^{116} (508 kev), the latter again not accessible by other means. The persistent peak at 342 kev is due to the presence of oxygen and results from the O$^{18}(\alpha,n\gamma)$Ne^{21} reaction, as pointed out previously.[11] Once again, the systematic trend of the level positions stands out. In the odd-A isotopes, the known 340-kev level ($I=3/2^+$) was excited in Cd^{111}; this level is known to decay predominantly to the ground state,[13] and the transition probability was computed accordingly. An interesting situation exists in Cd^{113}, whose one neighboring isobar, In^{113}, is stable, whereas the other neighbor, Ag^{113}, decays without gamma-ray emission. We have found a gamma ray of 290 kev in Cd^{113} and have shown it to be the first excited state of that nucleus by its excitation function. The absence (?) of gamma radiation in the decay of Ag^{113} would favor a $5/2^+$ spin assignment for that level. The latter cannot be the 5-year isomer of Cd^{113} because of the multipolarity of the transition. We find some slight evidence for another state at 550 kev. A state in that vicinity has been reported from a study of the Cd$^{112}(d,p)$Cd^{113} Q-values.[14] If we see this same state, it too cannot be the isomeric level. A summary of the results on Cd can be found in Table I.

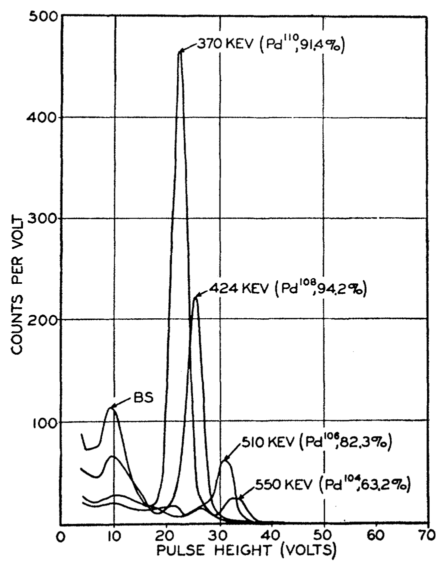

FIG. 1. Pulse-height spectra obtained for gamma rays from enriched even-even Pd isotopes under 6-Mev alpha-particle bombardment. $1\frac{3}{4}$ in.$\times$2 in. NaI crystal. Gamma-ray energies, responsible isotopes and target enrichments are indicated over each peak. Peak BS is due to backscattered gamma rays.

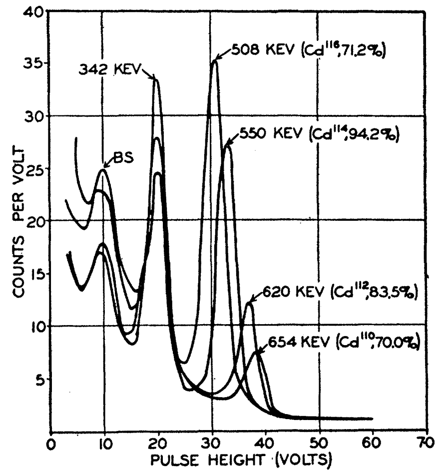

FIG. 2. Pulse-height spectra obtained for gamma rays from enriched even-even Cd isotopes under 6-Mev alpha-particle bombardment. $1\frac{3}{4}$ in.$\times$2 in. NaI crystal. Gamma-ray energies, responsible isotopes and target enrichments are indicated over each peak. Peak BS is due to backscattered gamma rays. Peak at 342 kev, always present in oxide targets, is due to O$^{18}(\alpha,n\gamma)$Ne^{21} reaction. Excess at that position in Cd^{110} target is due to 18.6 percent Cd^{111} component. To compare peak heights of these CdO targets with metallic Pd targets in Fig. 1, they must be raised by 35 percent (see text).

The accuracy in the energy determinations of the gamma rays is about ± 1 percent. The over-all uncertainty in the final values of the transition probabilities is estimated at ± 30 percent in *absolute* value; the relative values for the series of Pd and Cd isotopes are less uncertain (± 15 percent).

As was mentioned above, a definite trend in the size of the even-even transition probabilities can be dis-

TABLE I. Properties of excited states of Pd and Cd nuclei Coulomb-excited with 6-Mev alpha particles. I_0 and I^* are ground-state and excited-state spins and parities, respectively; $B(E2)$ is the reduced transition probability; Q_0 is the intrinsic quadrupole moment derived from $B(E2)$. $B(E2)$ refers to the *upward* transition.

Nucleus	I_0	I^*	E_γ (kev)	$B(E2)$ (10^{-48} cm^4)	Q_0 (10^{-24} cm^2)
$_{46}$Pd^{104}	0^+	2^+	550	0.61	2.5
Pd^{105}	$5/2^+$	$?^+$	266	0.013	...
		$?^+$	433	0.18	2.0^a
Pd^{106}	0^+	2^+	510	0.73	2.7
Pd^{108}	0^+	2^+	424^b	0.80	2.8
Pd^{110}	0^+	2^+	370^b	0.94	3.1
$_{48}$Cd^{110}	0^+	2^+	654	0.66	2.6
Cd^{111}	$1/2^+$	$3/2^+$	340	0.16	2.0
Cd^{112}	0^+	2^+	620	0.70	2.6
Cd^{113}	$1/2^+$	$(5/2^+)$	290^b	0.080	1.2
		$?^+$	(550)	0.14^c	...
Cd^{114}	0^+	2^+	550	0.73	2.7
Cd^{116}	0^+	2^+	508^b	0.76	2.8

^{a} Computed by assuming $I^*=7/2^+$.
^{b} Level previously unknown.
^{c} Represents upper limit.

[13] C. L. McGinnis, Phys. Rev. **81**, 734 (1951).

[14] N. S. Wall, Phys. Rev. **96**, 664 (1954).

cerned, increasing monotonically with increasing neutron number, while the excitation energies of the 2^+ states decrease. According to the simplest "strong coupling" approximation in the unified description of the nucleus,[15,16] which identifies the 2^+ state with the first rotational state of a deformed nucleus, this is just as expected: in both Pd and Cd we are moving away from the closed shell at $N=50$ toward greater deformation, i.e., larger values of the intrinsic quadrupole moment Q_0. The nuclei of $_{48}$Cd are presumably somewhat less deformed than those of $_{46}$Pd because their proton number lies closer to the shell at $Z=50$. Now the *position* of the 2^+ state is *inversely* proportional to $Q_0^2(E_{2^+}=6\hbar^2/2\mathscr{I}; \mathscr{I}\sim Q_0^2)$, while the (upward) *transition probability* to the 2^+ state is proportional to $Q_0^2[B(E2)=5/16\pi(e^2Q_0^2)]$.[15,16] The values of Q_0 obtained from the transition probabilities are listed in the last column of Table I. The values are quite comparable to those we found previously for the odd-Z nuclei $_{45}$Rh^{103}, $_{47}$Ag^{107}, and $_{47}$Ag^{109},[7] as well as to the spectroscopically measured Q_0 in $_{49}$In^{115}. It is just such continuity of nuclear properties which seems to support the unified model. The values of Q_0 as derived from the moments of inertia (level positions) follow the same trend but turn out to be about three times larger, a tendency which has been previously noted.[15,17] All transition probabilities are about twenty times greater than would be predicted on the basis of a single-particle transition.

Since all these nuclei have spins of either 0 or $\frac{1}{2}$ (except Pd^{105}), their intrinsic quadrupole moments are not accessible to conventional measurement. The equivalent lifetimes for the transitions we observe here range between 2 and 7×10^{-11} second.

We have obtained additional results in even-even nuclei of Ti, Fe, Zn, Ge, Se, Ru, and Mo, to be published at a later date.

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[15] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[16] A. Bohr, "Rotational states of atomic nuclei," dissertation, Copenhagen, 1954 (unpublished).
[17] K. W. Ford, Phys. Rev. **95**, 1250 (1954).

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Gamma Rays from the Low-Energy Proton Bombardment of Beryllium†

R. R. CARLSON AND E. B. NELSON
State University of Iowa, Iowa City, Iowa
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The gamma radiation produced in the Be$^9(p,\gamma)$B^{10} reaction at proton energies of approximately 300 kev was investigated with scintillation spectrometers. A three-crystal scintillation spectrometer detected 6.7 ± 0.15, 6.0 ± 0.1, 5.1 ± 0.1, and 4.7 ± 0.15-Mev gamma rays with relative intensities (±25 percent) of 0.15, 0.40, 1.00 and 0.45, respectively. A thick target yield of $(1.2\pm0.3)\times10^{-10}$ gamma per proton at 315-kev proton energy was measured for gamma radiation of 5.1-Mev energy. These gamma rays are produced in transitions to the ground-state and low-lying levels in B^{10} and their relative intensities and yield imply spin 1^- for the level at 6.89 Mev. A limited single-crystal spectrometer detected 0.41 ± 0.02, 0.72 ± 0.02, 1.03 ± 0.03, and 1.43 ± 0.03-Mev gamma rays corresponding to transitions between the low-lying levels in B^{10}. The angular correlation of the 0.72- and 1.03-Mev gamma rays was found to be consistent with a spin of 1^+ or 2^+ for the first excited state of B^{10}.

INTRODUCTION

THE energy levels of the B^{10} nucleus have been studied in a number of nuclear reactions. The results are summarized in the review article by Ajzenberg and Lauritsen.[1] Briefly, low-lying levels at 0.72, 1.74, 2.15, and 3.58 Mev are very well established, having been deduced from inelastic scattering experiments with protons and deuterons (with the exception of the 1.74-Mev state in the case of deuterons). Also, the first level has been seen in the reaction C$^{12}(d,\alpha)$B^{10}; the first and second, in the beta decay of C^{10}; the first, second, and third, in the reaction Li$^7(\alpha,n)$B^{10}. A level at 4.78 Mev has appeared in the inelastic proton scattering work. The above-mentioned levels and levels at 5.11, 5.17, 5.37, 5.58, 5.72, 5.93, 6.12, 6.38, 6.58, and 6.77 Mev appear in work on the neutron groups from Be$^9(d,n)$B^{10}. Further levels resulting from proton capture resonances in Be^9 show up at 6.89, 7.03, 7.19, 7.48, and 7.56 Mev.

The ground-state spin of B^{10} is known[2] to be 3 and the parity even.[3] Sherr and Gerhart[4] present various arguments to show that the first, second, third, and fourth excited states have spins and parities of 1^+, 0^+,

† Supported in part by the U. S. Atomic Energy Commission.
[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952). See also forthcoming supplement in the Reviews of Modern Physics. We wish to thank Professor Lauritsen for a preprint of the supplement.
[2] Gordy, Ring, and Burg, Phys. Rev. **78**, 512 (1950).
[3] F. Ajzenberg, Phys. Rev. **88**, 298 (1952).
[4] R. Sherr and J. B. Gerhart, Phys. Rev. **91**, 909 (1953).