Coulomb Excitation Studies Using Inelastically Scattered Particles*

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Targets of samarium, terbium, and cadmium were bombarded with protons, and in one case with deuterons, of up to 7.0 Mev and the inelastically scattered particles were observed. In the rare earths, samarium and terbium, four previously known levels were studied: the 58- and 139-kev levels in Tb^{159}, the 80-kev level in Sm^{154}, and the 123-kev level in Sm^{152}. The excitation process was determined to be primarily Coulomb excitation up to 7.0 Mev, and the reduced transition probabilities were measured with a precision of approximately 10%. A test of the collective model was made by measurement of the ratios of the reduced transition probabilities to two excited states in the same nucleus, Tb^{159}.

Eight levels were observed in cadmium. Two of them, at 585 and 641 kev, have not been previously reported. The absolute cross sections of the eight levels were determined with various angles of observation, incident energy, and type of bombarding particle. It was concluded that Coulomb excitation is a major contributor to the cross section at 6.0 Mev, and reduced transition probabilities were measured at this energy.

I. INTRODUCTION

THE study of the Coulomb excitation process by the observation of the inelastically scattered particles has several advantages over the usual methods involving the detection of the de-excitation gamma rays or their accompanying conversion electrons. These methods are often made difficult by the lack of precise information on the magnitudes of the conversion coefficients, as well as by the experimental difficulties of converting thick-target cross sections into cross sections at a unique energy. For the gamma-ray studies, there is the added difficulty of estimating detector efficiencies accurately. For the odd-A nuclei, where the second excited states are formed in Coulomb excitation and the decays are in general mixtures of $M1$ and $E2$ transitions, a knowledge of the mixture is essential for the determination of internal conversion. Added difficulties are encountered in correcting for the cascade to crossover ratios. These problems, among others, are discussed in two recent review articles,[1,2] which give excellent descriptions of the general techniques and results of Coulomb excitation studies.

For these reasons, it was thought that the study of this process through the examination of the ratio of inelastically to elastically scattered particles would be profitable. It would eliminate the above difficulties and could lead to inherently more precise measurements.

The magnetic spectrograph of the High Voltage Laboratory is a particularly suitable detection instrument for this type of work. It has high resolution so that the particles scattered from the low-lying levels can usually be separated from the elastically scattered particles. This is especially important in the rare earths where the low-lying rotational levels often have excitations of less than 100 kev. As used in conjunction with the beam from the Van de Graaff accelerator, simultaneous precise measurements of cross sections relative to the elastic cross section and of the excitation energies for the observable levels in a target nucleus are possible. By relating the elastic scattering cross section to the cross section for Rutherford scattering, these measurements of the inelastic to elastic cross-section ratios directly yield the absolute cross section of the level involved and eliminate the need for knowing the target thickness and detector solid angle or of making absolute current measurements.

The major experimental difficulties of this method are the necessarily small solid angle of the detector and the thin targets needed to resolve the inelastically scattered proton groups. This necessitates long exposures to get good statistics, and a considerable background of charged-particle tracks accumulates. These are caused by particles scattered from the target chamber and various slit edges. For those nuclei in the weak-coupling region with small quardupole moments, and hence small Coulomb excitation cross sections, the signal-to-noise ratio is dangerously low. In the rare-earth region, the cross sections for the excitation of the rotational levels are a factor of 2 or 3 larger and more precise measurements can be obtained.

Three elements were chosen to initiate the investigation, two rare earths and a medium-weight nucleus from the weak coupling area. The first, terbium, is a monoisotopic rare earth of odd-A, with which there would not be the difficulty of determining the particular isotope associated with the observed levels. Two gamma rays were observed at 79 and 136 kev by Temmer and Heydenburg[3] from Coulomb excitation in this element. These energies do not fit the predictions of the collective model for a theoretical ratio $E_2/E_1 = 2.4$. Other evidence

* This work has been supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] Alder, Bohr, Huus, Mottelson, and Winther, Revs. Modern Phys. **28**, 432 (1956).
[2] N. P. Heydenburg and G. M. Temmer, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1956), Vol. 6, p. 77.
[3] G. M. Temmer and H. P. Heydenburg, Phys. Rev. **100**, 150 (1955).

points to the fact that the 79-kev gamma ray results from a cascade, and Temmer and Heydenburg conclude that the levels are actually at 57 and 136 kev ($E_2/E_1=2.39$). The observation of the inelastically scattered protons gives the level scheme unambiguously, and it was hoped to check this conclusion, as well as to obtain a more precise value for the transition probabilities. The other rare earth, samarium, was chosen as an example of the second general type of level schematics as predicted by the collective model for even-even nuclei. Only the first excited states of these nuclei have been observed in the usual Coulomb excitation studies. Samarium has five even-even isotopes, which span $N=90$, the neutron number at which a discontinuity in the nuclear properties is evidenced.[4] The isotopes of sufficient abundance to be significant are Sm^{147}, 15%; Sm^{148}, 11.2%; Sm^{149}, 13.8%; Sm^{150}, 7.4%; Sm^{152}, 26.8%; and Sm^{154}, 22.7%. Only two levels have been observed in the bombardment of natural samarium targets in Coulomb excitation studies, a level at 82 kev in Sm^{154} and a level at 122 kev in Sm^{152}. The parent isotope of these levels has been identified, and other levels have been observed through the use of isotopically enriched targets.[3]

Cadmium was chosen as the other element to be studied. A summary of the known information, which is relevant to the present work, appears in the first five columns of Table I. Of the eight stable isotopes, only six are sufficiently abundant to be of importance in this experiment.

Similar measurements of the inelastically scattered particles resulting from Coulomb excitation in gold[5] and in several of the rare earths[6] and from a direct interaction process in indium[7] were made at this laboratory during the same period as these measurements and are reported elsewhere.

TABLE I. Low-lying levels in cadmium.

		Relevant energy levels (kev)			
Isotope	Percent abundance	Coulomb excitation studies[a]	Radioactivity[b] studies	Other work	Present work
Cd^{110}	12.4	654	656, 1420, 1540, and higher		659
Cd^{111}	12.8	340	340, 420		346
Cd^{112}	24.0	619			619
Cd^{113}	12.3	290 550?		$Cd^{112}(d,p)$ 550[c]	300
Cd^{114}	28.8	550	548, 715	$Cd^{113}(n,\gamma)$ 550, 1200, 1280, and higher[d]	558
Cd^{116}	7.6	508			514
?	...	...	...	...	585
?	...	...	...	...	641

[a] Some levels were reported by both Mark, McClelland, and Goodman [Phys. Rev. **98**, 1245 (1955)] and G. M. Temmer and N. P. Heydenburg [Phys. Rev. **98**, 1308 (1955)]; the values quoted are from Mark *et al.*
[b] M. Goldhaber and R. D. Hill, Revs. Modern Phys. **24**, 179 (1952).
[c] N. S. Wall, Phys. Rev. **96**, 664 (1954).
[d] Adyasevich, Groshev, and Demidov, *Proceedings of the Conference of the Academy of Sciences of the U. S. S. R. on the Peaceful Uses of Atomic Energy, Moscow, July, 1955* (Akademiia Nauk, S. S. S. R., Moscow, 1955) [English translation by Consultants Bureau, New York: U. S. Atomic Energy Commission Report TR-2435, 1956], Phys. Math. Sci. p. 270.

II. APPARATUS AND PROCEDURE

The source of accelerated charged particles was the MIT-ONR Van de Graaff accelerator. The emergent beam was deflected through 90 degrees by a uniform-field magnet and was collimated by a slit system which defined the incident energy. It then passed through the target. The charged particles that emerged from the target were analyzed by a broad-range magnetic spectrograph,[8] in which they were again deflected through a mean angle of 90 degrees, dispersed according to their momentum, and recorded on photographic plates. The spectrograph can be rotated about an axis through the target from zero to 130 degrees with respect to the beam direction. The unscattered part of the beam, after passing through the thin target, was collected in a Faraday cup, and the total charge was measured with a current integrating circuit.

Targets were prepared by the evaporation of small samples of the rare-earth oxides and of cadmium metal onto thin films of Formvar which were supported by rectangular wire frames. Targets approximately 10-kev thick to 7.0-Mev protons were prepared which later withstood bombardment of up to 0.1 microampere. Long bombardments of about 1000 or 2000 microcoulombs were made with incident protons and, in one case, with deuterons.

The intensities of the various groups were measured by counting the total number of tracks with a low-powered microscope. An estimated background correction was applied. The elastic groups from the target materials were so dense as to be uncountable in these long exposures, and shorter exposures were made using other areas of the photographic plate before, after, and usually once or twice at intervals during the course of the long exposures. This was done as a check on changes in target thickness and other experimental conditions.

The ratio per microcoulomb of the intensities of the various inelastic groups to the elastic group was determined, and the absolute cross sections were obtained from the theoretical Rutherford scattering intensity calculated for the elastic group.

Separate measurements were made to determine the variation of the elastic scattering cross section with energy, and it was compared with the predictions of Rutherford scattering. Exposures at 130 degrees and at 5.0, 5.5, 6.0, and 7.0 Mev were made on the rare earths and to within the experimental uncertainties the cross sections varied as $1/E^2$. Exposures at 130 degrees

[4] G. Scharff-Goldhaber and J. Weneser, Phys. Rev. **98**, 212 (1955).
[5] B. Elbek and C. K. Bockelman, Phys. Rev. **105**, 657 (1957).
[6] B. Elbek (to be published).
[7] R. D. Sharp and W. W. Buechner, Bull. Am. Phys. Soc. Ser. II, **2**, 179 (1957).
[8] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. **27**, 899 (1956).

TABLE II. Ratios of elastic cross sections to Rutherford cross sections for cadmium.

Energy	Angle	Incident particle	Ratio to Rutherford	Percent standard deviation
7.0	130°	p	0.82	2.6
7.0	130°	d	0.59	2.9
6.0	130°	p	0.94	2.4
7.0	105°	p	0.92	2.4

and at 4.0, 5.0, 6.0, and 7.0 Mev on cadmium showed a deviation from Rutherford scattering at the higher energies and a correction to the absolute cross section was necessary. The ratio of the elastic cross sections, corresponding to the energy, angle of observation, and type of bombarding particle of each of the long exposures, to the elastic cross section at the lower energies (4.0 and 5.0 Mev) where the variation was as $1/E^2$, was measured. The correction factors thus obtained are given in Table II.

The Q value of each inelastically scattered group was calculated from its separation on the plate from the elastically scattered group. The values quoted are precise within 10 kev. The groups from contaminants and elements in the target backing were identified by their shifts of position along the plate with changes of bombarding energy and angle of observation.

In the terbium exposures, it was not found practicable to go any farther forward than 130 degrees, since the first level was only just resolved from the elastic peak even at that angle, and the groups merge at smaller angles. The light contaminant elastics could be identified by their shifts with respect to incident energy, but the heavier contaminants shift by about the same amount as the terbium inelastic peaks and were differentiated from them by their increased cross sections at the lower bombarding energies.

III. RESULTS AND CONCLUSIONS

Terbium

Long exposures were made at 130 degrees and 7.0, 6.0, and 5.0 Mev incident energies using the terbium targets. The 7.0-Mev data are shown in Fig. 1. Two known levels were identified at 58 and 139 kev. No other levels were observed, although small amounts of contaminants present in the rare-earth samples obscured regions of the plate in the neighborhood of 450-kev excitation.

The absolute cross sections were computed as indicated above and are listed in Table III. They have been corrected for an estimated 1% gadolinium contaminant content. The errors quoted are compounded from the standard deviation and an estimate of the error involved in the subtraction of the background. The latter is taken as the percentage change in the intensity for a 25% error in the estimate of the background. These are considered to be the major experimental errors involved.

From the absolute cross sections, one can calculate the reduced transition probabilities for electric quadrupole excitation under the assumption that the excitation process is pure $E2$ Coulomb excitation. This quantity $B(E2)$ is related to the partial lifetime for quadrupole gamma decay through Coulomb excitation theory and to the intrinsic quadrupole moment of the nucleus[1,2] through the theory of the collective model. Values of $B(E2)/e^2$ are shown in Table III, as computed from the classical approximation to the Coulomb excitation theory as tabulated by Alder *et al.*[1] and by Alder and Winther.[9] The agreement of the three experimental values of this quantity within the expected error is an indication that Coulomb excitation is the dominant process up to 7.0 Mev. The weighted average of the three determinations gives the final values $B(E2)/e^2=3.56\pm0.32$ for the 58-kev level and $B(E2)/e^2=1.27\pm0.13$ for the 139-kev level. The value for the 139-kev level is in agreement with the weighted average of previous experimental determinations, as listed in Table IV.2 of reference 1. The value for the 58-kev level differs from the value (2.4) presented in this table. The value obtained in the present work is in good agreement with the conversion electron measurement of Huus, Bjerregard, and Elbek, whose value was one of the two used in obtaining the weighted average.

The agreement of the reduced transition probabilities at the three bombarding energies indicates the essential correctness of the theory of the Coulomb excitation process. The experiment also makes possible a check on the predictions of the collective model for the relative magnitudes of the transition probabilities to the two excited states. These transition probabilities should be related to the same quadrupole moment. This should be a rather sensitive test of the collective model, providing a direct check on the nuclear coupling schemes.[1] The ratio of the transition probabilities can be determined directly in these experiments from the ratio of the total number of tracks in two peaks on the same

TABLE III. Rare-earth cross-section measurements.[a]

Isotope	E_{in} (Mev)	θ_{lab}	Excitation energy (kev)	Absolute cross section mb/sterad	$B(E2)/e^2$ (10^{-48} cm^4)	Weighted average
Sm^{154}	7	130	80	1.68	3.43 ± 0.41	3.45 ± 0.40
Sm^{154}	7	90	80	2.07	$3.7\ \pm1.7$	
Sm^{152}	7	130	123	1.43	2.96 ± 0.40	3.20 ± 0.36
Sm^{152}	7	90	123	2.25	4.10 ± 0.80	
Tb^{159}	7	130	58	1.57	3.49 ± 0.45	
Tb^{159}	6	130	58	1.39	3.63 ± 0.65	3.56 ± 0.32
Tb^{159}	5	130	58	1.16	3.64 ± 0.66	
Tb^{159}	7	130	139	0.58	1.32 ± 0.19	
Tb^{159}	6	130	139	0.44	1.21 ± 0.27	1.27 ± 0.13
Tb^{159}	5	130	139	0.37	1.21 ± 0.28	

[a] Errors quoted are standard deviations.

[9] K. Alder and A. Winther, CERN Report T-KA-AW-1, October, 1954 (unpublished).

plate from the same exposure. The weighted average of the ratios from the three exposures is 0.36 ± 0.05. This is to be compared with the theoretically predicted value of 0.56. The value found here differs from the experimental value of 0.56 as presented in Table V.4 of reference 1, which gives a compilation of the measured values of this ratio found in various nuclei.

Deviations of about this magnitude from the predicted values of the collective model are found in other nuclei in this region, as can be seen in the abovementioned table and in the results of Goldring and Paulissen[10] who have made a systematic study of this ratio in several nuclei using a coincidence technique.

Samarium

The targets of natural samarium were exposed at 7.0 Mev at 130 and 90 degrees. The 130-degree data are shown in the figure. Two levels were observed at 80 and 123 kev in agreement with the energies of levels found in previous Coulomb excitation studies using isotopically enriched targets by Temmer and Heydenburg[3] among others. No higher excited states or states in the less abundant isotopes were observed. The Q values and the cross sections were computed assuming the responsible isotopes were those found by these authors. The shift from 130 to 90 degrees was made rather than varying the bombarding energy, because the yields are largest at the higher energy, and the first state was of high enough excitation to be resolved from the elastic peak at 90 degrees. This also facilitated the identification of the peaks from contaminants. The added background associated with the intense group of protons elastically scattered from samarium did, however, considerably increase the uncertainty in the value of the cross section of the 80-kev level obtained from the 90-degree exposure.

The cross sections and transition probabilities determined from these measurements are shown in Table III. The errors were calculated as before. The $B(E2)/e^2$ values obtained from the two exposures agree within the precision of the measurement, and this fact, together with the results for terbium, is taken to indicate that the process is largely Coulomb excitation and that the transition probabilities are therefore meaningful. The weighted averages are $B(E2)/e^2=3.45\pm0.40$ for the 80-kev level and $B(E2)/e^2=3.20\pm0.36$ for the 123-kev level. The value obtained here for the 123-kev level is in good agreement with the value presented in Table IV.2 of reference 1. The result for the 80-kev level differs from their weighted average of $B(E2)/e^2=4.5$.

Cadmium

The cadmium targets were initially bombarded with 7.04-Mev protons, and the reaction products were observed at 130 and 105 degrees. The 130-degree data are shown in the figure. Eight levels were identified in

[10] G. Goldring and G. T. Paulissen, Phys. Rev. **103**, 1314 (1956).

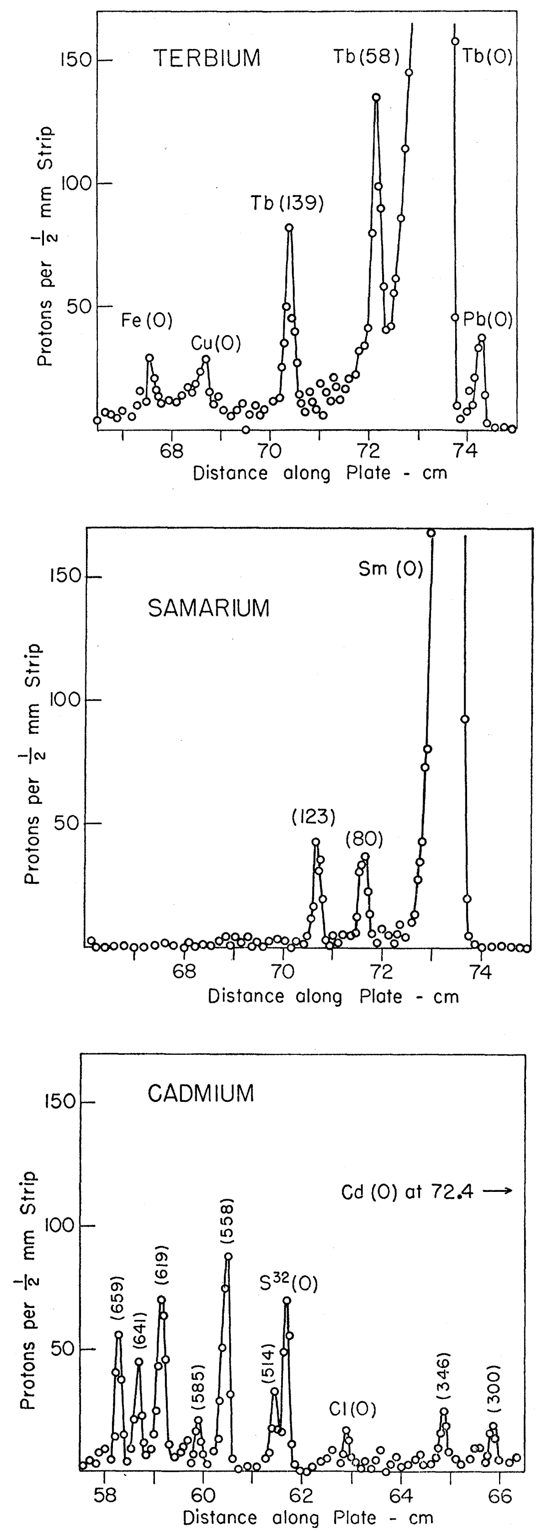

FIG. 1. Portions of the spectra of protons scattered at 130 degrees from terbium, samarium, and cadmium targets. In each case, the incident proton energy was 7.0 Mev. The individual proton peaks are labeled with the energy (in kev) of the levels with which they are associated.

TABLE IV. Cross-section measurements on cadmium.[a]

Exposure conditions E_{in}	θ	I.P.	Excitation energy (kev): Assumed isotope:	300 113	346 111	514 116	558 114	585 ?	619 112	641 ?	659 110
7	130°	p	σI	0.017	0.027	0.033	0.14	0.024	0.11	0.046	0.068
			σ	0.14	0.21	0.43	0.49	...	0.47	...	0.54
			E	26	22	20	10	19	10	21	12
7	130°	d	σI	0.027	0.027	0.058	0.25	0.040	0.22	<0.008	0.079
			σ	0.22	0.21	0.77	0.86	...	0.92	...	0.64
			E	17	16	10	10	12	10	...	10
6	130°	p	σI	<0.01	<0.01	0.028	0.078	0.014	0.051	0.013	0.025
			σ	...	...	0.37	0.27	...	0.21	...	0.20
			E	...	...	23	13	36	32	39	23
7	105°	p	σI	...	...	0.055	0.18	0.052	0.12	0.046	0.083
			σ	...	...	0.72	0.61	...	0.50	...	0.67
			E	...	...	21	10	19	10	19	11

[a] σ =absolute cross section in millibarns/steradian, I =isotopic abundance of parent isotope of level, E =estimated percentage error, E_{in} =incident energy (Mev), θ =angle of observation (lab), I.P. =type of incident particle, proton or deuteron.

the region between 300 and 700 kev (see Table I). Two of these levels were previously unknown. No other levels were observed in the region of excitation examined, which was from the ground state to approximately 4 Mev. The Q values shown in the table were calculated using the isotopic mass for each of the known levels, as had been determined in measurements on enriched isotopes.[11] The parent isotope of each of the two new levels is unknown. The Q values of these levels were calculated, assuming masses of both 110 and 116 to give the limiting values. For mass 110, the excitations were 579 and 637 kev. For mass 116, they were 592 and 648 kev. The average values, 585 and 641 kev, are used in the tables and in subsequent calculations. The uncertainty introduced by the unknown mass value is less than the quoted precision of ± 10 kev.

In order to obtain information about the nature of the excitation, it was first decided to study the variation of the cross section with energy. An exposure at 130 degrees and 5.99 Mev resulted in rather small yields. Rather than to decrease the energy still further, it was decided to measure the cross section for inelastic deuteron scattering. This should be larger than the proton cross section for a Coulomb excitation process in this region (see Fig. III.2 in reference 1). Consequently, an exposure with deuterons was made at 130 degrees and 6.91 Mev.

The groups associated with the 300-kev and 346-kev levels observed in the 7.04-Mev exposure were not observed in the 5.99-Mev exposure, nor was the group for the 641-kev level observed in the deuteron exposure. Upper limits on their intensities are given. The 300- and 346-kev groups were interfered with by small elastic peaks from chlorine in the 105-degree exposure and were not used in the calculations. All the other levels were observed in the four different exposures.

The ratio of the inelastic to elastic cross sections was obtained, and the absolute cross sections were computed, as indicated previously. The Rutherford scattering cross section was assumed to be the same for all the isotopes. The absolute cross sections of the two new levels are not determinable until experiments with separated isotopes are performed. The case of the 558-kev level in Cd^{114} is also in some doubt. It is uncertain from the measurements[11] whether or not there is also a level of this energy in Cd^{113}. If this were so, the cross section reported here, assuming the level to originate entirely in Cd^{114}, would be in error.

For these reasons, the experimental results are presented in Table IV as σI, where I is the isotopic abundance. This is the quantity actually determined in these experiments. The following line of the table contains the absolute cross section assuming the parent isotope as noted. The errors quoted are compounded from the standard deviation and an estimate of the

TABLE V. Ratios of cross sections for various changes in experimental conditions.[a]

Excitation (kev)	300	346	514	558	585	619	641	659
σ_6/σ_7								
Measured	<1.4	<1.0	0.87±0.26	0.57±0.09	0.60±0.25	0.47±0.16	0.25±0.11	0.39±0.10
Calculated	0.83	0.83	0.79	0.78	0.78	0.77	0.77	0.76
$\sigma_{105}/\sigma_{130}$								
Measured	...	...	1.7±0.5	1.2±0.1	2.2±0.6	1.1±0.2	1.0±0.3	1.2±0.2
Calculated	1.08	1.08	1.09	1.09	1.09	1.10	1.10	1.10
σ_d/σ_p								
Measured	1.5±0.5	1.0±0.3	1.8±0.4	1.7±0.2	1.6±0.4	1.9±0.2	<0.3	1.2±0.2
Calculated	1.9	1.9	1.7	1.7	1.7	1.7	1.7	1.7

[a] σ_6/σ_7 =variation of bombarding energy from 6 to 7 Mev; for proton scattering at 130 degrees; $\sigma_{105}/\sigma_{130}$ =variation of angle of observation from 105 to 130 degrees, for proton scattering at 7 Mev; σ_d/σ_p =variation of scattered particle from protons to deuterons, at 7 Mev and 130 degrees.

[11] G. M. Temmer and N. P. Heydenburg, Phys. Rev. 98, 1308 (1955).

background error as before. In consideration of other experimental errors, an estimated uncertainty of 10% was quoted when the error calculated as indicated above was less than this value.

It is convenient to examine the experimental results in the form of cross-section ratios and to compare them with the expected ratios from the Coulomb excitation process (see Table V). The theoretical ratios were calculated as before from the classical approximation tabulated in reference 1. in Table V, σ_6/σ_7 refers to the ratio of cross sections for a change of from 6- to 7-Mev bombarding energy for proton scattering at 130 degrees; σ_d/σ_p refers to the ratio of the cross sections for a change of incident particle from deuterons to protons at 7 Mev and 130 degrees; and $\sigma_{105}/\sigma_{130}$ refers to the ratio of the cross sections for a change of angle of observation of from 105 to 130 degrees for proton scattering at 7 Mev.

It does not appear justifiable to conclude from these ratios that Coulomb excitation is the only excitation process that contributes to the cross sections. In particular, the σ_6/σ_7 ratios are all low, except for one. A cross section increasing with energy slightly faster than as predicted for Coulomb excitation would seem to indicate a competing process beginning to be important in this range. That the effects of this competing process are not dominant even at 7 Mev is indicated by the fact that the σ_d/σ_p ratios are nearly as predicted for five of the levels. The 641-kev level, in fact, does disappear with deuteron bombardment, and therefore it appears to be excited almost completely by this competing process. This would explain why it has not been observed in the previous Coulomb excitation studies. It can be seen from the ratios that the reduced transition probabilities calculated from the different experiments will not be in agreement. The 6-Mev results should give the value, since Coulomb excitation is expected to become more dominant as the energy is decreased. Since many of the ratios are not very far from those expected, even at 7 Mev, the 6-Mev transition probabilities are expected to be approximately correct. For the observed levels of known isotopic parentage, they are

Excitation (kev)	514	558	619	659
$B(E2)/e^2$ (10^{-48} cm^4)	0.68	0.52	0.42	0.42.

This is in excellent agreement with the lastest results of Temmer and Heydenburg,[12] who find in a region of pure Coulomb excitation:

Excitation (kev)	508	550	620	654
$\epsilon B(E2)/e^2$ (10^{-48} cm^4)	0.62	0.55	0.46	0.41.

The conversion coefficients are small for these transitions, and the correction term ϵ is approximately unity.

It therefore appears that the transition region between Coulomb excitation and other processes begins in cadmium at approximately 7 Mev. This is not surprising, since in the neighboring nucleus, indium, a direct interaction process becomes important in this energy range and in fact appears to be the dominant excitation mechanism at 7 Mev.[7]

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[12] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).