Electric Excitation of Certain Medium-Weight Nuclei by Protons*

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(Received February 24, 1955)

Electric excitation has been used to study energy levels in sixteen elements ranging from scandium to iodine. Seventeen γ rays have been observed. Electric quadrupole transition probabilities for the energy levels corresponding to these γ rays have been calculated from the measured electric-excitation cross sections. The results are substantially larger than those expected from transitions of single particles but are significantly and uniformly lower than those calculated from the energies of the levels by using the hypothesis of rotational excitation. Similar observations have been made previously for a series of heavy nuclei. It is suggested that this effect results from either a nonuniform distribution of charge and mass in the nucleus or from a breakdown of the assumption that the collective motion can be represented as an irrotational flow.

I. INTRODUCTION

THE usefulness of electric excitation for studying nuclear structure has been demonstrated effectively in recent months.[1–3] Measurements of electric-excitation cross sections have been used to determine electric multipole transition probabilities for many nuclear energy levels, and in some cases it has been possible to clarify uncertainties in energy level assignments by performing electric excitation experiments with enriched isotopes.[2,3] Since the cross section for electric excitation of a nuclear energy level is proportional to its electric multipole transition probability, this method of excitation is particularly useful for studying those levels with large transition probabilities (that is, short half-lives). The "collective" model of nuclear structure[4] predicts the existence of nuclear energy levels which have large electric quadrupole transition probabilities. Since most of the energy levels reported in this work have transition probabilities that are appreciably larger than those expected from transitions of single particles, our results serve as a qualitative confirmation of the validity of the collective model in this region of the periodic table.

II. EXPERIMENTAL METHODS

The experimental methods used are simple. A target of the material under investigation is bombarded by monoenergetic protons from the MIT-Rockefeller electrostatic generator. The energy of the protons is determined, using the $Li^7(p,n)$ threshold at 1881.4 kev[5] as a calibration point. The existence of nuclear excitations were detected by measuring the γ rays emitted from the target during bombardment. A NaI(Tl) single-crystal scintillation spectrometer was used to measure both the energy and the intensity of the γ rays emitted. This unit consisted of a 2 in.$\times$2 in. Harshaw Chemical Company "canned" NaI(Tl) crystal bonded optically with a thin film of clear Nujol oil to the face of a DuMont 6292 photomultiplier tube. The pulses from this unit were fed through a wide-band amplifier (Model 100) and a single-channel pulse-height analyzer (AIC Model 510). The energy standards used for calibrating the unit fall into two categories; radioactive sources and γ rays from various targets bombarded with protons. The radioactive sources were: Cs^{137}, 661 kev;[6] Na^{22}, 511 kev; and Co^{57}, 123 kev.[7] The γ rays at 303 and 137 kev[8] from electric excitation of Ta^{181} and the x-rays of Ta at 57 kev and Pb at 75 kev[9] were also used. Energies quoted are accurate within about 8 percent. The intensity of a γ ray (and hence the cross section for production) was determined either by comparing the yield to a calibrated source placed at the target position or by using the extensive calculations of Maeder, Muller, and Wintersteiger[10] to determine the efficiency of the detector. All counting rates were monitored by a beam current integrator which was calibrated by a standard battery. The proton current was known within 5 percent.

The axis of the crystal was mounted perpendicular to the direction of the proton beam, and the front face was about 5 cm from the target for all measurements. This geometry was necessary in order to shield the unit from the collimating apertures of the machine. An inch of lead was sufficient to reduce the background from this source to a very low level.

Several types of targets were used. The thick targets consisted either of metal sheets or of metallic and metallic-oxide powders that were compressed into a small depression in a lead or tin backing disk. The thin targets were obtained by evaporating the material

* This work has been supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] T. Huus and A. Lunden, Phil. Mag. **45**, 966 (1954).
[2] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **95**, 861 (1954).
[3] McClelland, Mark, and Goodman, Phys. Rev. **93**, 904 (1954).
[4] A. Bohr and B. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **27**, No. 16 (1953).
[5] Jones, Douglas, McEllistrem, and Richards, Phys. Rev. **94**, 947 (1954).
[6] Muller, Hoyt, Klein, and DuMond, Phys. Rev. **88**, 775 (1952).
[7] D. E. Alburger and M. A. Grace, Proc. Phys. Soc. (London) **A67**, 280 (1954).
[8] T. Huus and J. Bjerregard, Phys. Rev. **92**, 1579 (1954).
[9] A. H. Compton and S. K. Allison, *X-Rays in Theory and Experiment* (D. van Nostrand Company, Inc., New York, 1935).
[10] Maeder, Muller, and Wintersteiger, Helv. Phys. Acta **27**, 3 (1954).

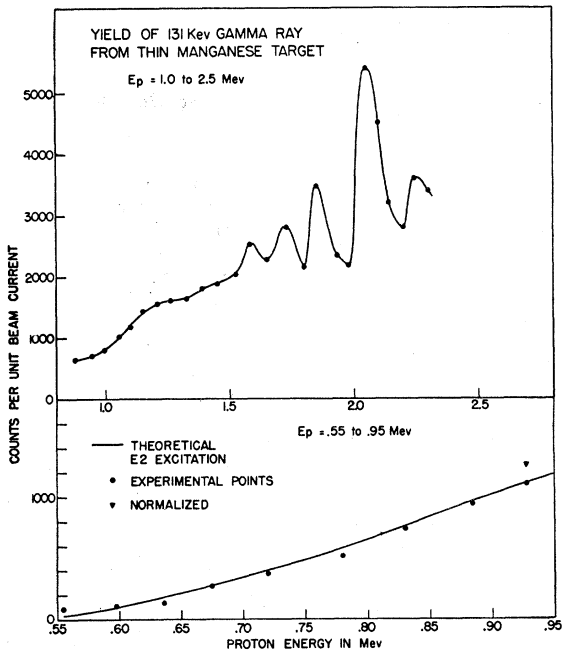

FIG. 1. The yield of the 131-kev γ ray from a thin manganese target as a function of proton energy. In the region below 1 Mev, the excitation curve agrees well with the expected electric quadrupole excitation function, while above 1 Mev the strong resonance structure indicates that the γ ray is produced by a process involving formation of a compound nucleus.

either on a tin or a lead backing. For thin-target cross-section measurements, the thickness was determined by measuring the stopping power using the "sandwich" target technique of Madsen *et al.*[11] and then calculating the number of atoms per square centimeter from published data.[12]

Impurities in the target materials often yield γ rays which interfere with the measurements. A common impurity in many materials is sodium which gives rise to a strong γ ray at 439 kev[13] from $Na(p,p'\gamma)$. Aluminum, fluorine, and oxygen are also troublesome sources of γ rays in the energy region of interest. In most cases, cleaning the surface of metallic targets and extensive leaching with hot distilled water of the powdered metals before preparing the targets eliminated the worst effects. Impurity effects will be discussed in greater detail in the section dealing with each element separately.

Characteristic x-rays and proton bremsstrahlung are important background effects whenever protons are used as bombarding particles in electric-excitation experiments.[14] In the region of the periodic table under consideration, the energy of the x-rays is so small that they are effectively absorbed by 0.04 inch of cadmium placed between the target and the crystal. Proton bremsstrahlung, which is the subject of a forthcoming paper, is not so easily eliminated. The effect makes it difficult to observe weak γ rays below 150 kev and also contributes to the error in determining energies of intense lines.

Once it has been determined that a given γ ray originates in the element being bombarded, it must be ascertained whether the γ ray is the result of an electric-excitation process or of a process involving penetration of the Coulomb barrier. For heavy nuclei ($Z>60$), the Coulomb barrier is so large that for 4.0-Mev protons there is no appreciable penetration. For lighter elements, this is not the case and a measurement of the yield of the γ ray as a function of proton energy must be made to determine the process from which it originates. Figure 1 shows the yield of the 131-kev γ ray from a thin manganese (Mn^{55}) target. Below 1 Mev, the curve agrees well with the calculated electric quadrupole excitation function, indicating that electric excitation is the dominant process in this region. The strong resonance structure in the yield above 1 Mev shows that the energy level is formed mainly by compound nucleus inelastic scattering of protons. The yields of the 315- and 418-kev γ rays from thick and thin silver targets are shown in Fig. 2. In this case, because of the relatively large value of the nuclear charge, barrier penetration is not very important. Both yield curves agree reasonably well with the theoretical

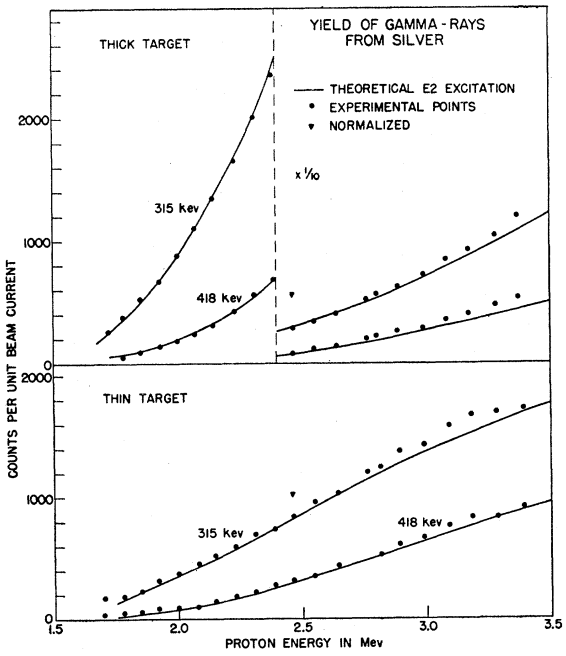

FIG. 2. The yield of the 315- and 418-kev γ rays from thick and thin silver targets. The curves for both γ rays agree well with the theoretical electric quadrupole excitation function. The thick target used in these measurements was about 80 kev thick to 2-Mev protons.

[11] C. B. Madsen and P. Venkateswarlu, Phys. Rev. **74**, 648 (1948).
[12] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).
[13] Donahue, Jones, McEllistrem, and Richards, Phys. Rev. **89**, 824 (1953).
[14] C. Zupančič and T. Huus, Phys. Rev. **94**, 205 (1954).

electric quadrupole excitation function over the whole energy range. It should be pointed out that a measurement of the excitation curve is not a particularly sensitive method for determining the multipole order of a given γ ray. It is important to rule out all other processes of excitation of the level, because it is only legitimate to calculate the transition probability from the cross section if electric excitation is the primary cause of formation.

III. EXPERIMENTAL RESULTS

Sixteen elements (scandium, vanadium, chromium' manganese, cobalt, zirconium, niobium, molybdenum, palladium, silver, cadmium, indium, tin, antimony, tellurium, iodine) were bombarded. Seven of these elements (scandium, cobalt, zirconium, niobium, tin, antimony, tellurium) showed no γ rays which could be attributed to electric excitation with reasonable certainty when bombarded with protons up to 2.75 Mev. The other elements studied showed γ rays ranging in energy from 131 to 610 kev. In three cases (chromium, palladium, cadmium), samples of enriched isotopes were bombarded in order to determine isotopic assignments of observed γ rays.

Vanadium.—Targets made of spectroscopically pure (Massey Ltd.) V_2O_5 were bombarded with 1.5-Mev protons. A γ ray was observed at 325 kev, which probably arises from a level at about this energy in 99 percent abundant V^{51}, observed previously by Kurie and Ter-Pogossian[15] and Temmer and Heydenburg.[16] Since compound nucleus formation is probably the dominant process in the excitation of this level at 1.5 Mev, it is not possible to calculate the transition probability from the cross section. This γ ray could not be observed at bombarding energies less than 1.3 Mev.

Chromium.—Targets made of Cr_2O_3 were bombarded with protons between 1.0 and 1.8 Mev. No γ rays attributable to electric excitation were observed from the natural Cr_2O_3 target. A weak γ ray at 155 kev is observed when 90.06 percent enriched $Cr_2{}^{53}O_3$ targets are bombarded with 1.3-Mev protons. The reaction $Cr^{53}(p,n\gamma)Mn^{53}$ may be ruled out as the source of this γ ray, since the threshold for this reaction is greater than 1.4 Mev.[17] It is possible that this γ ray originates in Cr^{53}, but it is difficult to confirm this assignment. The yield of the γ ray as a function of proton energy does not agree too well with the characteristic electric-excitation yield curve, but this is expected since compound nucleus formation certainly contributes to the formation of this level. The assignment of this line must therefore be considered doubtful.

Manganese.—The energy-level structure of Mn^{55} has been studied previously by inelastic scattering of protons[18] and electric excitation with α particles.[16] Both methods reveal the existence of an excited level at roughly 130 kev. The yield of this γ ray from thin Mn^{55} targets has been studied as a function of proton energy (see Fig. 1). The measured yield begins to get larger than the one predicted by electric excitation above 1 Mev, since compound nucleus formation begins to be appreciable in this region.[19]

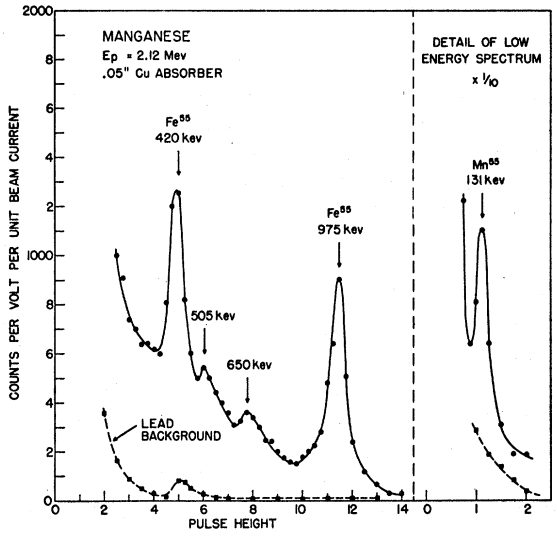

FIG. 3. The pulse-height spectrum obtained from a thin manganese target bombarded with 2.12-Mev protons. The peak at 131 kev is due to de-excitation of the level in Mn^{55} following inelastic proton scattering. The two peaks at 420 and 975 kev probably come from γ rays following the reaction $Mn^{55}(p,n\gamma)Fe^{55}$. Possible origins of the 505- and 650-kev peaks are discussed in the text. The small peak at 440 kev in the background curve is due to a sodium impurity in the lead backing on which the manganese was evaporated. A 0.05-inch copper absorber was used to attenuate the lead x-rays.

The pulse-height spectrum produced by γ rays from a thin manganese target during bombardment with 2.12-Mev protons is shown in Fig. 3. Peaks corresponding to γ rays having energies of 131, 420, 505, 650, and 975 kev are observed. The 420- and 975-kev γ rays probably come from the $Mn^{55}(p,n\gamma)Fe^{55}$ reaction and are due to the first two excited levels[20] in Fe^{55}. The 975-kev γ ray could also come from an excited level in Mn^{55} at approximately 1 Mev reported by Housman *et al.*[18] The origin of the 505- and 650-kev lines is not quite clear. Housman *et al.*,[18] and Temmer and Heydenburg[16] do not report any levels in Mn^{55} at these energies; hence, it is unlikely that they arise from inelastic proton scattering. It is possible that the weak line at 505 kev represents the cascade transition between the 975- and 420-kev level in Fe^{55}, although its energy is somewhat too low. The 650-kev line could be due to

[15] F. N. D. Kurie and M. Ter-Pogossian, Phys. Rev. **74**, 677 (1948).
[16] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **96**, 426 (1954).
[17] McClelland, Goodman, and Stelson, Phys. Rev. **86**, 631 (1952).
[18] Housman, Allen, Arthur, Bender, and McDole, Phys. Rev. **88**, 1296 (1952).
[19] M. Shapiro, Phys. Rev. **90**, 171 (1953).
[20] P. H. Stelson and W. M. Preston, Phys. Rev. **82**, 655 (1951).

the peak in the Compton distribution from the 975-kev line.

The cross section for the production of 131-kev γ rays with 0.940-Mev protons was measured by comparing the yield of this γ ray from a target of known thickness with the γ yield of a calibrated Co^{57} source placed at the position of the target. The energy of the γ ray from this source (123 kev) is similar to the energy of the Mn^{55} γ ray, and therefore a direct comparison of the two photopeaks is justified. The target thickness was measured by the "sandwich" target method of Madsen *et al.*,[11] using the sharp double resonance in the $Al(p,\gamma)$ yield at about 1.4 Mev. The data of Chilton *et al.*[21] on the stopping power of copper and nickel were used to calculate the number of atoms per square centimeter.

Molybdenum.—Three γ rays (199, 440, and 525 kev) are observed when a powdered molybdenum metal target is bombarded with 2.46-Mev protons. The γ ray at 199 kev has been observed previously by Temmer and Heydenburg[22] and is probably due to electric excitation of a level at about this energy in Mo^{95} which has also been observed[23] in the positron decay of Tc^{95}. The origin of the 440- and 525-kev γ rays is not clear. It is probable that the 440-kev line is due to a sodium impurity in the target. The 525-kev line has been observed by Temmer and Heydenburg[24] using 6-Mev α particles. The isotopic assignment of this line is in doubt.

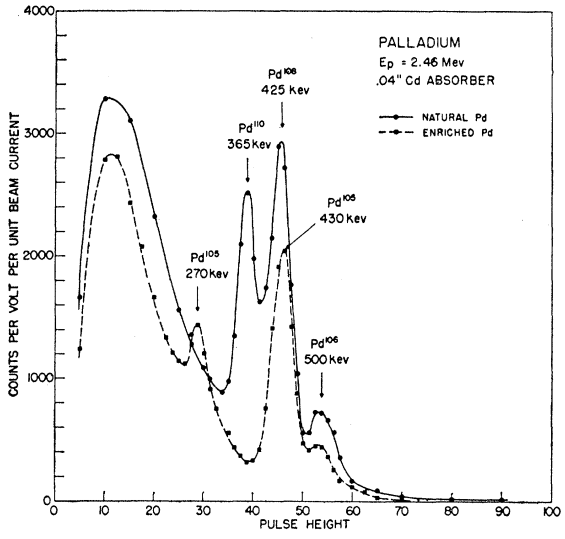

FIG. 4. The pulse-height spectra obtained when natural Pd and enriched Pd^{105} targets are bombarded with 2.46-Mev protons. The principal isotopes present in the enriched Pd^{105} target are Pd^{105}, 78.19 percent, and Pd^{106}, 16.04 percent. The peak at 425 kev from the natural Pd target is a composite line caused by γ rays of nearly equal energies in Pd^{105} and Pd^{108}. A 0.04-inch Cd absorber was used to attenuate the palladium x-rays. The broad low-energy pulse distribution is due to proton bremsstrahlung.

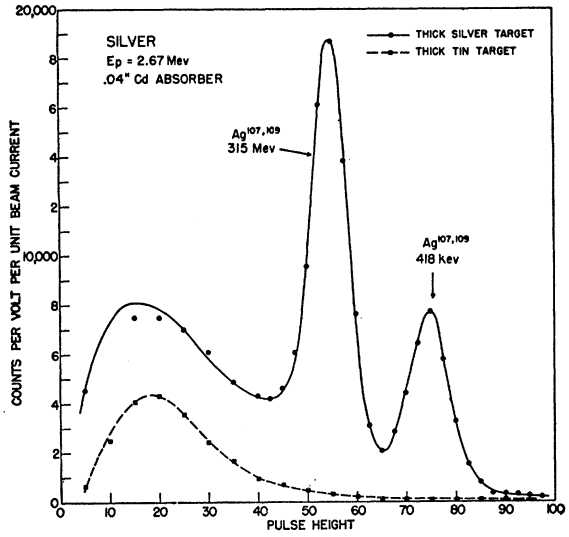

FIG. 5. The pulse-height spectrum obtained from a thick silver metal target bombarded with 2.75-Mev protons. The peaks at 315 and 418 kev are composite lines caused by γ rays of nearly equal energies from both silver isotopes. A pulse-height spectrum obtained from a thick tin target under similar conditions is shown to demonstrate the background effects caused by proton bremsstrahlung. The characteristic x-rays of both materials are almost entirely absorbed by a 0.04-inch cadmium sheet placed between the crystal and the target.

Palladium.—The pulse-height spectrum produced by γ rays from powdered Pd and enriched Pd^{105} targets during bombardment with 2.46-Mev protons is shown in Fig. 4. Peaks corresponding to γ rays having energies of 365, 425, and 500 kev from natural Pd and 270, 430, and 500 kev from enriched Pd^{105} are observed. The 270-kev line is caused by electric excitation of Pd^{105} and probably corresponds to the known level at 282 kev in this isotope which is observed[25] in the K-capture decay of Ag^{105}. The line at 500 kev is due to electric excitation of 27.1 percent abundant Pd^{106} and can also be identified with a known level in this isotope at 505 kev which is observed[25] in the K-capture decay of Ag^{106}. The 500-kev γ ray is also observed from the enriched Pd^{105} sample with about 0.6 the intensity of the γ ray from the natural Pd, since the enriched sample contains 16.04 percent Pd^{106}. The 425- and 430-kev γ rays are more difficult to assign to the proper isotopes. The most probable interpretation is that the 430-kev γ ray seen in the enriched Pd^{105} comes from electric excitation of a level in Pd^{105} at this energy,[25] while the 425-kev γ ray seen in natural Pd is a composite line caused partially by excitation of the 430-kev level in 22.6 percent abundant Pd^{105} and of a known level at about this energy in 26.7 percent abundant Pd^{108} which is

[21] Chilton, Cooper, and Harris, Phys. Rev. **91**, 495 (1953).
[22] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **93**, 351 (1953).
[23] Huber, Medicus, Preiswerk, and Steffen, Phys. Rev. **73**, 1211 (1948).
[24] G. M. Temmer and N. P. Heydenburg (private communication).
[25] Deutsch, Roberts, and Elliott, Phys. Rev. **61**. 389 (1942).

observed[26] in the K-capture decay of Ag^{108}. The 365-kev line in natural Pd is due to electric excitation of a level in 13.5 percent abundant Pd^{110} which has been identified by Temmer and Heydenburg.[24]

Silver.—The γ rays (315 and 418 kev) emitted when thick silver metal targets are bombarded with 2.75-Mev protons are shown in Fig. 5. These energy levels have been studied extensively by Huus and Lunden[1] and Temmer and Heydenburg.[2] The lines shown are due to the superposition of γ rays of nearly equal energies coming from both isotopes. The cross section for the production of these γ-rays was measured using both thick-target yield data and thin-target methods described for manganese. The reasonable agreement between the results is good evidence that the techniques used in obtaining the cross section from the thick-target yield are probably valid. The large absolute error in these measurements, which is due primarily to the estimation of the detector efficiency, does not alter this conclusion, since the same corrections were applied to both thick- and thin-target yields.

Cadmium.—The pulse-height spectra produced when targets of CdO, enriched $Cd^{111}O$, and enriched $Cd^{113}O$ are bombarded with 2.46-Mev protons are shown in Fig. 6. The γ ray at 330 kev is due to electric excitation of a level in Cd^{111} at about this energy which is observed[27] in the β^- decay of Ag^{111}. The line at 610 kev which appears in the enriched sample and also in the natural target is due to electric excitation of a level in Cd^{112}. The 290-kev peak is caused by electric excitation of a level in Cd^{113} and the line at 545 kev which appears in the enriched $Cd^{113}O$ sample and also in natural CdO is due to electric excitation of Cd^{114}. This γ ray corresponds to a known level in Cd^{114} at 548 kev which is observed[28] in the K-capture decay of In^{114}. It is improbable that the 420- and 500-kev γ rays observed from all three targets arise from electric excitation of any Cd isotope. They are probably the result of bombardment of oxygen with protons, since they appear with roughly equal intensities from all targets. (The reaction $O^{16}(p,\gamma)F^{17}$ could give rise to 500-kev γ rays coming from cascade between the 4.35- and 3.86-Mev levels in the decay of F^{17}.)

Indium.—A 500-kev γ ray is observed when a thick indium metal target is bombarded with protons. This γ ray has been observed by Temmer and Heydenburg[22] and probably arises from a known level in In^{115} at this energy.[29]

Iodine.—A fairly intense 212-kev γ ray is observed when compressed PbI targets are bombarded with 2.0-Mev protons. This line has been observed previously by Temmer and Heydenburg[22] and also by inelastic scattering of neutrons from iodine.[30] The PbI targets were quite difficult to work with, since PbI sublimes readily at low temperatures. The cross section for the production of this γ ray could therefore not be measured. It was not possible to observe the 60-kev level in this nucleus[22] because of the strong interference from characteristic lead and iodine K-series x-rays.

The cross sections obtained for the production of all the above-mentioned γ rays are listed in Table I. The absolute errors in the cross sections are due to the following causes: 1. error in estimating detector efficiency; 2. error caused by possible anisotropy of emitted γ rays; 3. error in estimating stopping powers of the various materials; 4. errors in graphical subtractions of bremsstrahlung background; 5. error in calibrating activity of standard source; 6. error in calibration of beam current integrator. The most accurate measurement is the cross section for the 131-kev γ ray in Mn^{55}, since this result does not include a calculation of the detector efficiency. The other measurements, except for the γ ray in iodine, are considered reliable to within a factor of 2.

IV. INTERPRETATION

The reduced transition probability, $B(E2)$, for the levels can now be calculated from the observed cross

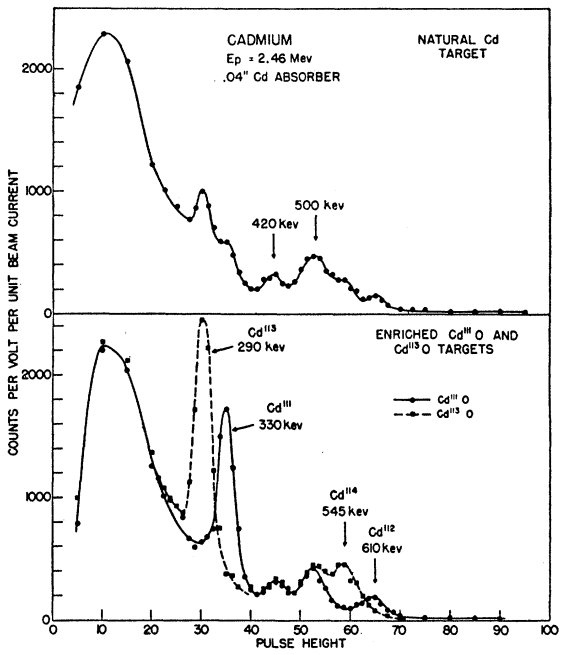

FIG. 6. The pulse-height spectra obtained when natural CdO, enriched $Cd^{111}O$, and enriched $Cd^{113}O$ targets are bombarded with 2.46-Mev protons. The principal isotopes present in the $Cd^{111}O$ target are Cd^{111}, 64.5 percent and Cd^{113}, 26.9 percent and the principal isotopes present in the Cd^{113} target are Cd^{113}, 54.1 percent and Cd^{114}, 37.9 percent. The peaks at 420 and 500 kev that appear in all three spectra are probably the result of some process following the bombardment of oxygen with protons. The broad low-energy pulse distribution is due to proton bremsstrahlung.

[26] Perlman, Bernstein, and Schwartz, Phys. Rev. **92**, 1236 (1953).
[27] S. Johansson, Phys. Rev. **79**, 896 (1950).
[28] F. Boehm and P. Preiswerk, Helv. Phys. Acta **22**, 331 (1949).
[29] Cork, Rutledge, Stoddard, Branyan, and LeBlanc, Phys. Rev. **79**, 938 (1950).
[30] R. M. Kiehn and C. Goodman, Phys. Rev. **95**, 989 (1954).

TABLE I. Summary of results. Column 3 lists the proton energy at which the cross-section measurement for each level was made. In column 6, the spin change of the transition is shown for those cases in which it is known or can be reasonably inferred from the collective model. Column 7 shows the value of $B(E2)$ for the excitation of the levels obtained from the measured cross sections shown in columns 4 and 5 and from the measured energies shown in column 2.

Nuclide	Measured excitation energy (kev)	Proton energy (Mev)	σ(thin) millibarns	σ(thick) millibarns	$I_0 \rightarrow I$	$B(E2)$ in $\text{cm}^4 \times 10^{-49}$ from $\sigma(E2)$	from ΔE
V^{51}	325	1.50	···	0.1	7/2→?	···	···
Cr^{53}	155(?)	1.50	···	0.12	7/2→?	0.15	···
Mn^{55}	131	0.94	0.29±0.11	···	5/2→?	0.87	···
Mo^{95}	199	2.46	···	0.043	5/2→?	0.57	···
Pd^{105}	270	2.46	···	0.02[a]	5/2→?	0.084	···
	430	2.75		0.10[a]	5/2→?	0.57	···
Pd^{106}	500	2.75	···	0.080	0→2	1.8	49
Pd^{108}	425	2.75	···	0.15[b]	0→2	2.1	58
Pd^{110}	365	2.75	···	0.10	0→2	2.6	67
$Ag^{107,109}$	315	2.75	0.27[b]	0.24[b]	1/2→3/2	0.79	18
	418	2.75	0.20[b]	0.19[b]	1/2→5/2	0.86	27
Cd^{111}	330	2.75	···	0.010	1/2→3/2	0.27	···
Cd^{112}	610	2.75	···	0.028	0→2	1.3	43
Cd^{113}	290	2.75	···	0.020	1/2→3/2	0.58	···
Cd^{114}	545	2.75	···	0.050	0→2	1.4	48
In^{115}	500	3.00	···	0.010	9/2→?	0.58	···
I^{127}	212	2.00	···	···	5/2→?	···	···

[a] Enriched isotope target.
[b] Composite line.

sections. All excitations are assumed to be electric quadrupole. The formula used is one proposed by Alder and Winther[31] in which a WKB approximation of the Coulomb wave function describing the motion of the projectile is used to calculate the matrix elements. The cross section for electric quadrupole excitation is:

$$\sigma(E2)=\frac{2\pi^2}{25}\frac{m_1 v_f^2}{Z_2^2 e^2 \hbar^2}B(E2)g_{E2}(\xi), \tag{1}$$

and

$$\xi=\frac{Z_1 Z_2 e^2}{\hbar}\left[\frac{1}{v_f}-\frac{1}{v_i}\right]. \tag{2}$$

The notations used above are identical to those used in reference 31. The functions $g_{E2}(\xi)$ are taken from curves which these authors have kindly sent to us. Equations (1) and (2) give results that are somewhat different from earlier calculations based on the semiclassical treatment of Ter-Martirosyan.[32] We have purposely listed all measured cross sections in Table I so that our values of $B(E2)$ can be modified as improvements in the theory are made.

The values of $B(E2)$ calculated from (1) are listed in column 7 of Table I for those γ rays where the isotopic assignment is reasonably certain. Internal conversion has been ignored, since none of the conversion coefficients for any of the levels studied are greater[33] than 0.1. The possible cascade decay of any of the observed levels has also been ignored in the calculation of $B(E2)$.

[31] K. Alder and A. Winther, Phys. Rev. **96**, 237 (1954).
[32] K. A. Ter-Martirosyan, J. Exptl. Theoret. Phys. (U.S.S.R.) **22**, 284 (1952).
[33] M. E. Rose (private communication).

The "collective" model[4] predicts the existence of "rotational" energy levels that have three unique properties:

1. They possess reduced $E2$ transition probabilities, $B(E2)$, which are larger by at least an order of magnitude than those calculated for transitions of single particles from one orbit to another.
2. They exhibit an energy spectrum very similar to that of a rigid rotator.
3. The energy of the first excited level and its reduced $E2$ transition probability depend upon the same parameter; the ground-state deformation of the nucleus.

Condition 3 implies a unique relationship between $B(E2)$ and the energy of the first rotational level.

Following Bohr[34]:

$$B(E2)=\frac{\hbar^2 R_0^2 Z^2}{mA}K(I,I_0)\frac{1}{\Delta E}, \tag{3}$$

where R_0 is the nuclear radius, Z the nuclear charge, A the number of nucleons, m the mass of a nucleon, and ΔE the energy of the level. $K(I,I_0)$ is a numerical factor which depends upon the spins of the ground and first excited levels, I_0 and I. The last column in Table I shows the values of $B(E2)$ calculated from (3) by using the experimental energies ΔE.

The striking difference between the values of $B(E2)$ obtained from these two sources is a phenomenon that has already been observed in a series of heavy nuclei[35] and has also been deduced from a comparison of nuclear deformations obtained from electric quadrupole moments and isotope shift data and nuclear moments of inertia.[36] It has been suggested that this effect results either from a nonuniform distribution of charge and mass in the nucleus or from a breakdown of the hypothesis that the collective motion can be represented as an irrotational flow.

Several other comments may be made regarding the results shown in Table I. Since the reduced transition probability depends on the nuclear deformation, it is possible to calculate $B(E2)$ from the electric quadrupole moment of the nucleus. The only nuclide in Table I for which the quadrupole moment is known,[37] and for which the cross section has been measured, is In^{115}. The value of $B(E2)$ calculated from this quadrupole moment is 0.4×10^{-49} cm^4, which is in reasonable agreement with the value obtained from the electric excitation cross section shown in column 7 of Table I.

In two cases, Pd^{105} and the silver isotopes, it was possible to excite two levels in the same isotope. It is of interest therefore to compare the properties of the observed levels with the theoretical predictions of the

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collective model. In the case of the silver isotopes, both Ag^{107} and Ag^{109} have a ground-state spin of 1/2 and therefore do not exhibit a regular rotational spectrum.[4] However, the rotational (strong coupling) model does predict that the ratio of $B(E2)$ for the 315-kev transition to that of the 418-kev transition should be 0.66. This value is considerably smaller than the one obtained from the experimental cross-section measurement and is possibly a reflection of the fact that the transition probabilities obtained from the γ-ray measurement are distorted by possible cascade decay of the 418-kev level. The nuclide Pd^{105}, with a ground-state spin of 5/2, should exhibit a regular rotational spectrum if the collective model applies rigorously to this nucleus. If the first rotational level of Pd^{105} is at 270 kev, then the second level should be at about 617 kev, which is almost 200 kev higher than the observed energy of 430 kev. The values $B(E2)$ for these two levels are also inconsistent with those which would be expected if the rotational model were strictly valid for Pd^{105}. It is possible that the 430-kev level is actually the first rotational level in this isotope. The level at 270 kev would then not be strongly excited, and the peak that appears at this energy in Fig. 4 could arise from the cascade decay of the 430-kev level. A peak at 160 kev, which should accompany such a decay, would be hidden by the bremsstrahlung background.

The authors wish to express their thanks to Dr. C. P. Keim of the Oak Ridge National Laboratory for his aid in procuring the enriched isotopes and to Dr. Caspar Borkowski, also of Oak Ridge, for calibrating the Co^{57} source. We are also indebted to Dr. G. M. Temmer and Dr. N. P. Heydenburg for sending us some of their results prior to publication, and to Professor V. F. Weisskopf and Professor S. D. Drell for many useful discussions.

PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

Radionuclides Al^{24}, P^{28}, Cl^{32}, and Sc^{40}*

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(Received January 18, 1955)

Three new short-lived positron emitters, P^{28}, Cl^{32}, and Sc^{40} of the nuclear series $Z=2n+1$, $A=4n$ have been produced by p-n reactions using 20-Mev protons from the UCLA 41-in. FM cyclotron. Al^{24} has also been investigated. Al^{24} has a half-life of 2.10 $\pm$0.04 sec and five gamma rays from 1.39 Mev to 7.12 Mev. 2-Mev alpha particles are emitted in a small fraction of the decays. P^{28} has a half-life of 0.280 $\pm$0.010 sec, threshold of 15.6$\pm$0.5 Mev, eight gamma rays from 1.79 Mev to 7.59 Mev, and positrons of maximum energy 10.6$\pm$0.4 Mev. No heavy particles were detected in the decay. Cl^{32} has a half-life of 0.306$\pm$0.004 sec, threshold of 14.3$\pm$0.5 Mev, four gamma rays from 2.21 Mev to 4.77 Mev, and positrons of maximum energy 9.5$\pm$0.4 Mev. 2–3 Mev alpha particles are emitted in a small fraction of the decays. Sc^{40} has a half-life of 0.22$\pm$0.03 sec, threshold of 15.9$\pm$1.0 Mev, a 3.75$\pm$0.04 Mev gamma ray, and maximum positron energy of 9.0$\pm$0.4 Mev. No heavy particles were detected in the decay. Possible decay schemes can be set up which involve favored positron transitions to calculated analog levels in the daughters in the cases of Al^{24}, P^{28}, and Cl^{32}. In the P^{28} decay, the positron component to the 1.78-Mev level in Si^{28} has the same ft value as the negatron decay to this level from Al^{28}, thus indicating the similarity of the nuclear wave functions of P^{28} and Al^{28}.

I. INTRODUCTION

IN 1950 Alvarez[1] reported the discovery of the delayed alpha-particle emitters B^8, N^{12}, and Na^{20}, all members of the nuclear series $Z=2n+1$, $A=4n$. These nuclides are positron emitters which decay, at least partially, to an excited state of the daughter which in turn breaks up into an alpha particle and a residual nucleus. The lifetime of the excited state is extremely short compared to the lifetime of the parent, hence the apparent lifetime of the alpha activity is that of the parent. Alvarez also searched for F^{16}, the member between N^{12} and Na^{20}, but concluded that it was proton-unstable. Birge[2] subsequently reported the discovery of Al^{24}, the next member of the series. Al^{24} was produced by the $Mg^{24}(p,n)Al^{24}$ reaction and was detected by means of a heavy-particle activity. Both delayed alpha particles and delayed protons are energetically possible in the Al^{24} decay and it was not determined which occurred.

Mass estimates of possible additional members of the series, P^{28}, Cl^{32}, and Sc^{40}, placed them on the borderline of proton instability. A search for these nuclides and an investigation of their properties, and a further investigation of Al^{24}, has been carried out in this laboratory. The nuclides were produced by p-n reactions using 20-Mev protons generated in the UCLA 41-inch frequency-modulated cyclotron. Some earlier results of this investigation have been published.[3]

* Work supported by joint program of Office of Naval Research and U. S. Atomic Energy Commission. Part of a thesis submitted by N. W. Glass to the Graduate Division, University of California, Los Angeles, California, in partial fulfillment of requirements for the Ph.D. degree in Physics.

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