Coulomb Excitation of Neodymium*

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Three gamma rays produced by bombardment of neodymium metal with protons of energies up to 3.34 Mev have been observed. Measurements indicate gamma-ray energies and isotopic identifications of 71±4 kev from Nd^{145}, 300±3 kev from Nd^{148}, and 131±2 kev from Nd^{150}, with total cross sections for production of the last two radiations of 0.7±0.2 and 2.4±0.3 mb, respectively, for 2.25-Mev protons. Excitation functions found for the even-even iostopes agree with those predicted for $E2$ Coulomb interactions, leading to $0\rightarrow2+\rightarrow0$ level assignments; $E1$ excitation seems ruled out only for Nd^{150}. The theory of Alder and Winther for $E2$ excitation gives only qualitative agreement with the measured 131-kev gamma-ray angular distribution. Low-energy proton bremsstrahlung were also observed.

INTRODUCTION

THE use of Coulomb excitation and detection of the resulting gamma rays to investigate the positions, lifetimes, and spin and parity assignments of low-lying energy levels in medium-to-heavy nuclides is attractive in its complementary role with respect to beta-decay work. By this method it should be possible, in particular, to fill in some of the gaps in existing data upon the apparently quite regular variations of properties of even-even isotope level structures.[1] The results reported herein, of proton bombardment of neodymium isotopes just above the 82-neutron shell, confirm the expected trends of some of these regularities.

EXPERIMENTAL ARRANGEMENT

The experimental apparatus, set up in conjunction with the Minnesota electrostatic generator, consisted essentially of a thin-walled, 4-inch diameter, cylindrical aluminum reaction chamber (see Fig. 1) and a NaI(Tl) scintillation spectrometer. The 1-inch diameter by 1-inch long NaI(Tl) crystal was placed outside the chamber so that it subtended an angle $\sim9°$ at the target, and could be rotated about the chamber axis from laboratory angles of 23° to 147°. Extensive lead shielding reduced background from machine x-rays to a negligible amount.

The electronic equipment was of the non-overloading type, consisting of a Chase-Higinbotham pulse amplifier[2] and a 10-channel discriminator[3] preceded by a slightly modified Johnstone window amplifier.[4] One-volt channels were used throughout the experiment with good stability.

Targets were of 99.85 percent minimum purity neodymium metal[5] in the form of a $\frac{3}{16}$ inch thick metal sample and also foils made by evaporating neodymium onto thin nickel backings. The foils were thick to protons, yet thin to the gamma rays. A thick target of Nd_2O_3 enriched in Nd^{150} was also bombarded.[6]

EXPERIMENTAL RESULTS AND ANALYSIS

Gamma-ray spectra covering 30 to 800 kev exhibited three peaks due to gamma radiations from neodymium superposed upon a continuum of up to five times empty-chamber background. A typical spectrum is given in Fig. 2, which also depicts three other gamma-ray peaks. These latter peaks (A, B, and C), appearing only from the metal target and later removed by surface cleaning, were probably due to fluorine and sodium impurities. Table I lists the energy measurements of the neodymium peaks, as calibrated against a Hf^{181} gamma-ray source having peaks at 135, 345, and 481 kev;[7] these are compatible with the 136.5-kev assignment[8] to the lowest excited state in Ta^{181} and with the 37-kev peak from neodymium K x-rays. (This laboratory's earlier quoted value[9] for the 131-kev Nd gamma

TABLE I. A summary of data on gamma radiation excited by proton bombardment of neodymium.

E_γ kev	Source[a]	Percent natural abundance	σ_{total}[b] mb	τ[c] seconds	Q_0[d] barns
71±4	$_{60}Nd^{145}$	8.3	weak	...	...
300±3	$_{60}Nd^{148}$	5.7	0.7±0.2	2.6×10^{-10}	2.6
131±2	$_{60}Nd^{150}$	5.6	2.4±0.3	0.7×10^{-8}	4.0

[a] Identification by Temmer and Heydenburg (see reference 10) and by this laboratory.
[b] Cross section, corrected for natural abundance, for gamma-ray production at $E_p=2.25$ Mev.
[c] Estimated excited-state lifetime, assuming $E2$ Coulomb excitation.
[d] Estimated intrinsic quadrupole moment, assuming $E2$ Coulomb excitation.

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[1] G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953); F. Asaro and I. Perlman, Phys. Rev. **91**, 763 (1953); P. Stähelin and P. Preiswerk, Nuovo cimento **10**, 1219 (1953).
[2] R. L. Chase and W. A. Higinbotham, Rev. Sci. Instr. **23**, 34 (1952).
[3] W. C. Elmore and M. Sands, *Electronics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 241 ff.
[4] C. W. Johnstone, Nucleonics **11**, No. 1, 36 (1953).
[5] We are indebted to Professor F. H. Spedding of Iowa State College for making available the spectroscopically-analyzed neodymium metal.
[6] The neodymium oxide enriched in Nd^{150} was obtained from the Oak Ridge National Laboratory, Oak Ridge, Tennessee.
[7] Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953).
[8] Cork, Nester, LeBlanc, and Brice, Phys. Rev. **92**, 119 (1953).
[9] Simmons, Van Patter, Famularo, and Stuart, Bull. Am. Phys. Soc. **29**, No. 5, 15 (1954).

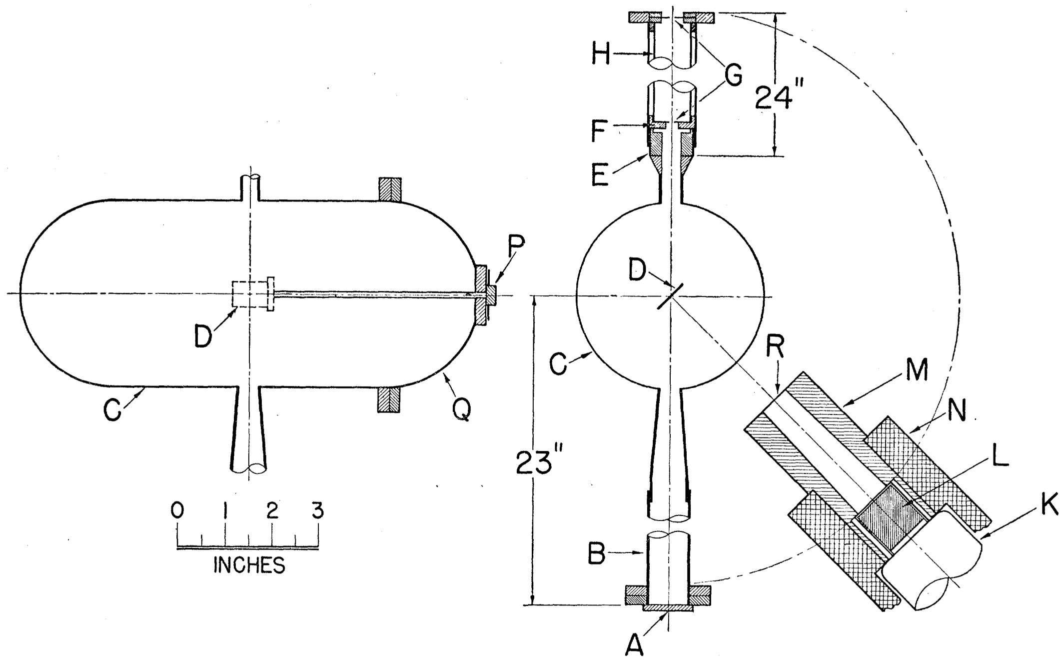

FIG. 1. Experimental apparatus, not showing extensive lead shielding used overall. *A*, quartz end window; *B*, beam exit tube, lined with nickel and tantalum; *C*, 32-mil aluminum chamber wall; *D*, target; *E*, Lucite insulator; *F*, Lucite spacer-insulator for slit system; *G*, two of four collimating slits (others not shown); *H*, steel tube containing tantalum lining and slits; *K*, DuMont 6292 photomultiplier tube; *L*, NaI(Tl) crystal; *M*, brass collimator-shield; *N*, lead shield; *P*, target angle adjustment; *Q*, removable end cap with target and holder. Chamber and exit tube are insulated for current collection, while the slit system is insulated separately to permit voltage biasing against secondary electrons. The counter rotates between the angles 23° and 147°.

ray is in error, having been assigned with reference to an impure Ce^{141} gamma-ray source.) The latest values[10] of Heydenburg and Temmer, who have previously reported these radiations,[11,12] are 70, 300, and 128 kev, in the order of listing of Table I.

Heydenburg and Temmer have bombarded neodymium oxides enriched in the isotopes Nd^{143}, Nd^{145}, and Nd^{148} with alpha particles and obtained the identifications listed in Table I.[10] Work here with protons and neodymium oxide enriched in Nd^{150} also indicated Nd^{150} to be the source of the 131-kev gamma rays.

The intensity of the 71-kev radiation was quite low and this gamma ray has not been further investigated. The 131- and 300-kev yields at 90° as functions of proton energy are shown in Fig. 3. The solid curves are least-squares fits for the theoretical total cross section $E2$ excitation functions as given by Alder and Winther.[13] The assumption here of isotropic angular distributions produces no significant error in the shape of these curves. A theoretical $E1$ excitation function,[14] shown in Fig. 3 as the broken curve, does not fit the data very well for the 131-kev radiation. This was fitted only to the low-energy data. However, the data for the 300-kev gamma rays can be fitted by either $E1$ or $E2$ excitation functions, the former not being shown in Fig. 2. In these and following computations, the stopping cross

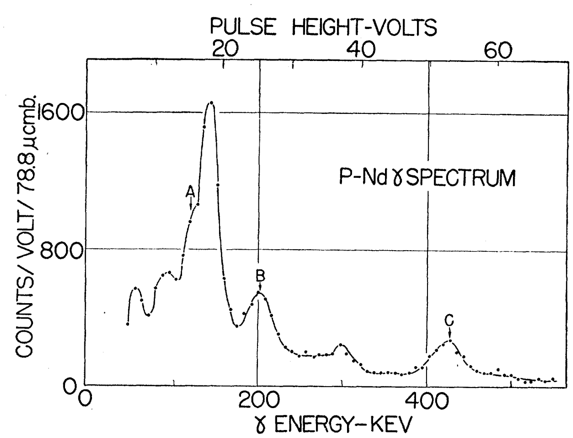

FIG. 2. A spectrum of the radiation emitted from a thick neodymium metal target when bombarded by 2.25-Mev protons; a 67-mil copper absorber was employed. The peaks *A*, *B*, and *C*, appearing only from this target and later removed by surface cleaning, are probably due to fluorine and sodium impurities. Gamma rays from neodymium give rise to the peaks at 71, 131, and 300 kev, while neodymium *K* x-rays form the low-energy peak. The underlying continuum is due principally to proton bremsstrahlung.

[10] N. P. Heydenburg (private communication).

[11] N. P. Heydenburg and G. M. Temmer, Phys. Rev. **93**, 906 (1954).

[12] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **94**, 1399 (1954).

[13] K. Alder and A. Winther, Phys. Rev. **91**, 1578 (1953).

[14] K. Alder and A. Winther (private communication).

section of neodymium for protons enters. Interpolated values for this were obtained by means of an approximate form of the Bethe-Bloch formula least-squares fitted to existing data[15,16] for copper, silver, and gold. Uncertainty in these values should have little effect upon the validity of the curves in Fig. 2, but do contribute ±7 percent probable error in estimates of absolute cross sections for neodymium.

The points in Fig. 4 give angular-distribution data obtained for the 131-kev gamma ray for 2.25-Mev protons incident upon a thick target, the large probable errors being due principally to uncertainty in background subtraction. The solid curve in Fig. 4 represents a three-parameter least-squares fit to the data, having a normalized form $1+0.00\cos^2\theta+0.27\cos^4\theta$. A theoretical angular-distribution estimate[14] of Alder and Winther, $1+0.55\cos^2\theta-0.22\cos^4\theta$ (not shown), fits the data only qualitatively. This assumes a $0\rightarrow 2+\rightarrow 0$ transition scheme for Nd^{150} and takes no account of the slight variation of coefficients with decreasing proton energy in the target. As a check to the neodymium data, the angular distribution of the Ta^{181} gamma ray was

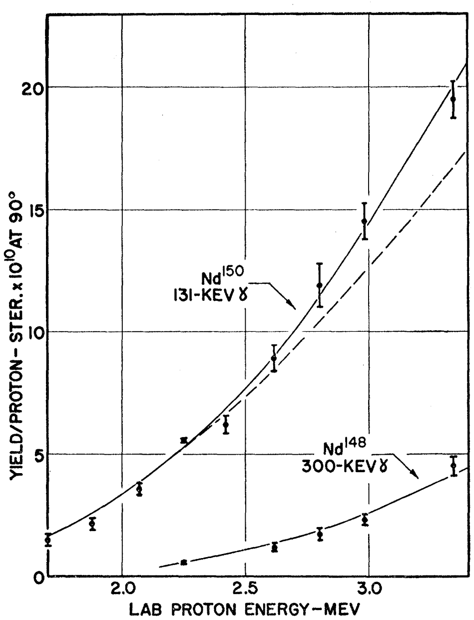

FIG. 3. Excitation functions for 300- and 131-kev gamma radiation excited by proton bombardment of neodymium. The data are uncorrected for NaI(Tl) crystal efficiency. The solid curves are least-squares fits to the data of the theoretical excitation functions, assuming *E*2 Coulomb interaction. The broken curve represents the theoretical *E*1 prediction for the 131-kev radiation, fitted to the data at the lower proton energies where its shape is almost that of the *E*2 curve. The theoretical *E*1 curve for the 300-kev data, not shown, would almost coincide with the corresponding *E*2 curve.

[15] S. K. Allison and S. D. Warshaw, Revs. Modern Phys. **25**, 779 (1953).

[16] R. Fuchs and W. Whaling, "Stopping Cross Sections," Kellog Radiation Laboratory, California Institute of Technology (unpublished).

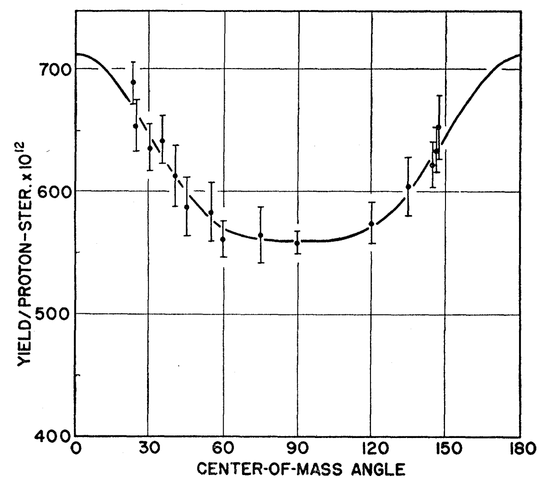

FIG. 4. The angular distribution for the 131-kev gamma radiation excited by proton bombardment of neodymium. The curve represents the function $560+000\cos^2\theta+150\cos^4\theta$, a least-squares three-parameter fit to the data; this has the normalized form $1+0.00\cos^2\theta+0.27\cos^4\theta$. The indicated probable errors are principally due to background subtraction.

measured to be isotropic to within 2 percent, in agreement with the results of others.[17,18]

Production cross sections for two of the observed gamma rays are given in Table I. These are based upon an assumed efficiency[19] for the NaI(Tl) crystal of 100 percent for the 131-kev gamma ray, and 77 percent for the 300-kev gamma ray. For the former all the counts were assumed[19] to fall under the photopeak; for the latter, 72±6 percent fell under the photopeak, the remainder making up the here-unobservable Compton distribution. The cross-section computation for the 131-kev radiation incorporates the three parameters from the best-fit angular-distribution curve, which are assumed to be constant with proton energy below 2.25 Mev. The 300-kev radiation is taken as isotropically distributed, an assumption which at worst, according to theory, should make the listed cross section 10 percent low. Lifetime estimates for the excited states are based upon *E*2 internal-conversion coefficients[20] of 33 percent and 7 percent for the Nd^{150} and the Nd^{148} levels, respectively. Intrinsic quadrupole moments computed on this basis by means of the Bohr-Mottelson theory[21] are also listed.

No indication of gamma rays from known levels[1,22] in Nd^{144} and Nd^{146} was found. The lower limits of observability indicate that the maximum cross section

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[18] Eisinger, Cook, and Class, Phys. Rev. **94**, 735 (1954).

[19] For these estimates and a thorough discussion of problems involved, see Maeder, Mueller, and Wintersteiger, Helv. Phys. Acta **27**, 3 (1954).

[20] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83, 79** (1951).

[21] A. Bohr and B. Mottelson, Kgl. Danske Videnskab. Selskab, Mat-fys. Medd. **14**, No. 16 (1954).

[22] Bernstein, Markowitz, and Katcoff, Phys. Rev. **93**, 1073 (1954).

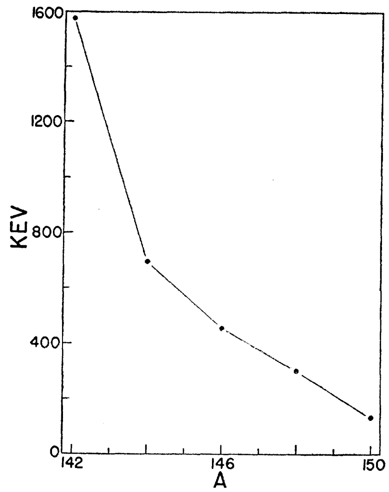

FIG. 5. The lowest-excited-state energies of the even-even isotopes of neodymium plotted against mass number A. Nd^{142} is magic in having 82 neutrons.

for production of a 455-kev gamma ray from Nd^{146} is about 1 mb at 2.79-Mev proton energy, and for production of a 695-kev gamma ray from Nd^{144} about 0.6 mb at 3.34 Mev. No search was made for a 1695-kev gamma ray[1] from Nd^{142}.

It is believed, in agreement with Zupančič and Huus,[23] that the continuum referred to at the beginning of this section is due to proton bremsstrahlung. Similar radiation was recorded from lead and from praeseodymium targets, which had no observable gamma-ray peaks in their spectra, and no change was observed after coating the inside of the chamber with Aquadag. The theory of Sommerfeld[24] give rough agreement with these data.

DISCUSSION

It appears probable that the levels excited in Nd^{148} and Nd^{150} should both have a 2+ assignment. Since the estimated cross section for compound-nucleus formation by 3.8-Mev protons is only 3×10^{-5} mb, the interaction force in this experiment should be essentially of Coulomb type. This leads to an excitation function dependent, in shape, only upon the nuclear properties charge, mass, and energy-level position, plus the relative spins of the levels involved in the excitation. The excitation function is, then, a measure of the number of units of angular momentum transferred during the interaction. This is the significance of the fit of the $E2$ excitation functions shown in Fig. 2. It will be noted that the relative parity of the levels is also established if these fits are unique.

The possibility of a magnetic interaction with these even-even nuclei seems unlikely, as does electric interaction of octupole or higher order. It is possible that $E1$ interaction could occur by means of an induced dipole moment in the target nucleus, but this seems improbable at least for Nd^{150} because of the poor fit to the data of the corresponding excitation function. For the Nd^{148} one cannot make a spin assignment on the basis of excitation-function fits, but even then the nuclear systematics indicate that in this region of A and Z the lowest excited state should be 2+.

The large probable errors associated with the angular distribution do not explain the seemingly real disagreement with the theory there, but it may be that some smearing from atomic motions occurs during the lifetime of the excited state. A recalculation now underway by Alder and Winther[14] of the numerical integrations in the theory may also lead to better agreement. Unfortunately no theoretical $E1$ angular distribution calculations are yet available for comparison.

The positions of the first excited states of all the stable even-even isotopes of neodymium are now believed known[1,22] and fall into the regular pattern depicted in Fig. 5. It seems likely that all of these levels are 2+, based upon the present data, upon the shape of beta spectra, upon decay schemes, and upon the known trend toward this property for even-even nuclei of medium and high mass. The computed intrinsic electric quadrupole moments are consistent with known moments for nearby odd-even nuclei.

[23] Č. Zupančič and T. Huus, Phys. Rev. **94**, 205 (1954).
[24] A. Sommerfeld, Ann. Physik (5) **11**, 257 (1931); for a complete listing of associated material see reference 23.