of the final data. Their contributions to this work are gratefully acknowledged.

APPENDIX

One hundred grams of potassium chloride enriched in potassium-40 was obtained on loan from the Stable Isotopes Division of Oak Ridge National Laboratory. This material had been produced by a long-term irradiation of potassium nitrate in the Materials Testing Reactor in order to enrich its potassium-40 content tenfold by radiative neutron capture in potassium-39. Following the irradiation, the sample had been converted to the chloride and it was being held for feed material for the electromagnetic-separation process.

The sample contained a readily perceptible amount of cesium-134, the only known long-lived activity of the alkali metals which can be produced by neutron capture. The amount of cesium-134 corresponded to the activation of a cesium impurity of $10^{-3\pm0.5}$ parts per million. The radiocesium was removed by the addition of cesium-chloride carrier, followed by the precipitation of cesium silicotungstate at 0°C. Two repetitions of this process sufficed to reduce the cesium activity to an imperceptible level.

Following the removal of the cesium, the sample exhibited a residual activity which was sufficient to reduce significantly the "peak-to-valley" ratio in the scintillation spectrum, as compared to that from a comparable weight of natural potassium chloride. In the absence of any definite clues to the identity of the residual activity, no further work was done on this sample and it was returned to Oak Ridge.

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Measurement of the Plane Polarization of Gamma Radiation*

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A simplified experimental technique, utilizing Compton scattering as the analyzing process, has been developed for the measurement of the plane polarization of gamma radiation emitted from oriented nuclei. Nuclei of Ce^{139} and Ce^{141} were aligned in a neodymium ethylsulfate lattice at low temperatures by the magnetic-hyperfine-structure method. The plane polarization of the emitted gamma radiation was measured as a function of temperature. The measured polarization of this radiation was found to be consistent with published results.

I. INTRODUCTION

A PLANE-POLARIZED quantum has associated with it an electric-field vector perpendicular to its direction of propagation and in the plane of polarization whose orientation is constant in space. This quantum inelastically interacts with an electron so that the quantum is preferentially scattered into a plane perpendicular to its electric field vector. An analogous situation is a dipole antenna which radiates preferentially in a plane perpendicular to its length. The Compton scattering of gamma radiation is therefore a polarization-sensitive process. A comprehensive review article on gamma-ray polarization and its detection is that by Fagg and Hanna.[1]

The plane polarization of gamma radiation emitted from oriented nuclei is ordinarily measured by using a polarimeter based on the one of Metzger and Deutsch.[2] This type of polarimeter basically consists of a scattering crystal (usually an organic scintillator) of low gamma-ray detection efficiency so that the impinging quantum is scattered only once, and two detection crystals [usually NaI(Tl) scintillators] of high gamma-ray detection efficiency and situated perpendicular to each other. The inherent limitation of this type of polarimeter is its over-all detection efficiency, since a majority of the quanta pass through the scattering crystal without interacting. This limitation is partially overcome with this new technique by utilizing the gamma-ray source *itself* as the scattering medium, and thus eliminating the need of a scattering crystal.

The plane polarization of the 166-keV gamma ray from the decay of Ce^{139} and the 142-keV gamma ray from the decay of Ce^{141} were measured as functions of temperature, using a Metzger-Deutsch type of polarimeter. These results have been published.[3] Then the plane polarizations of these gamma rays were measured as functions of temperature utilizing the new

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[1] L. W. Fagg and S. S. Hanna, Rev. Mod. Phys. **31**, 711 (1959).

[2] F. Metzger and M. Deutsch, Phys. Rev. **78**, 551 (1950).

[3] J. N. Haag, D. A. Shirley, and D. H. Templeton, Phys. Rev. **129**, 1601 (1963).

technique where the crystal containing the radioactive nuclei acted as the scatterer. A comparison was then made between the two sets of data.

II. EXPERIMENTAL APPARATUS

This polarimeter, schematically shown in Fig. 1, was utilized to measure the plane polarization of the 166-keV gamma ray of Ce^{139} and the 142-keV gamma ray of Ce^{141} in a low-temperature nuclear orientation experiment. The source in Fig. 1 is a 15-g single crystal of neodymium ethylsulfate containing the cerium nuclei in lattice sites. The source crystal is surrounded by the cylindrical glass cryostat encircled by two concentric coils of copper wire (not shown in Fig. 1) utilized for magnetic susceptibility measurements, and the two cylindrical Dewars of the orientation system. The anthracene scattering crystal of the standard polarimeter is replaced in this polarimeter by the source crystal itself, the 10-mil thickness of copper wire, the total 10 mm thickness of several glass walls, the liquid helium, and the liquid nitrogen of the orientation system. The two 1.0×1.5-in. NaI(Tl) detection crystals of the standard polarimeter are replaced by the two mutually perpendicular 3×3-in. NaI(Tl) detection crystals, the front face of each at 10 cm from the center of the source crystal. The two arrows A and B in Fig. 1 represent polarized gamma rays which have been preferentially Compton scattered into the NaI detectors.

Pulse-height analysis was performed separately on each NaI counter so that the appropriate Compton-scattered gamma-ray events could be selected from such events as Compton scattering of direct radiation in the NaI crystal itself. It should be explicitly noted that this type of polarimeter possesses the distinct advantage that no coincidence circuits are involved. Furthermore, no shielding of the two NaI crystals from direct radiation is required. More will be said about these easily met requirements later.

III. EXPERIMENTAL PROCEDURE

The nuclear reactions used to produce Ce^{139} and Ce^{141} are given in Table I. Following the irradiation, cerium was separated from the target material by oxidation to the +4 state, solvent extraction, and reduction to the +3 state.[4] It was then grown into the 15-g single crystal of neodymium ethylsulfate so that it replaced some of the Nd^{3+} ions. Finally, a layer of neodymium ethylsulfate was grown onto the surface of the crystal so that the cerium ions would not be located on the surface with its relatively higher temperature following an adiabatic demagnetization. The crystal was then mounted in a conventional nuclear orientation system.

The crystal was cooled by adiabatic demagnetization from 1.2°K and magnetic fields of up to 18 kG. The

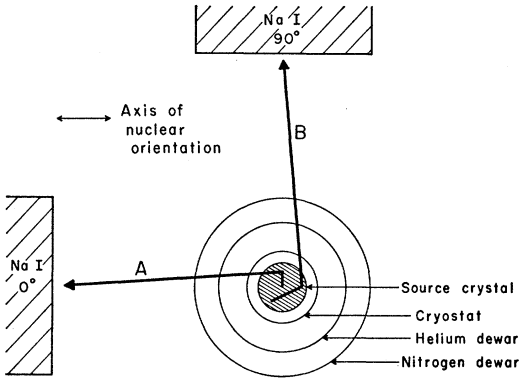

FIG. 1. Schematic of the simplified polarimeter.

magnetic temperature T^* of the crystal, as a function of time after demagnetizing, was determined by measuring the mutual inductance of the pair of coils surrounding the crystal. These values of T^*, when extrapolated to zero time, yielded a T_i^* which could be adjusted to the slightly different T_i^* from the data of Meyer[5] for an ellipsoidal neodymium ethylsulfate crystal. In other words, our crystal was only approximately ellipsoidal and a small constant correction was applied to our experimental T_i^* so that it equaled the T_i^* of Meyer for the same applied magnetic field. This constant correction was then applied to each of our experimental T^*. Utilizing Meyer's experimental relationship between T^* and T, we used our corrected T^* to find T for the crystal.

The intensity of the gamma rays was measured utilizing the two 3×3-in. NaI(Tl) crystals mentioned previously. A 256-channel pulse-height analyzer, split into two 128-channel units, was used to record the data. Following an adiabatic demagnetization, the gamma rays were counted for 6 min. Then the crystal was warmed to 1.2°K and a further 6-min normalization count was taken. The gamma radiation was isotropic within experimental error at this temperature. The gamma-ray intensity measurements were corrected for background. Since the low-temperature measurement and the 1.2°K measurement were separated in time, corrections were made for slight shifts in the gain of the counting system and for decay effects due to the half-lives. Since the low temperature and the 1.2°K intensities were different, a correction was also made for the different electronic "dead times" of the pulse-height analyzer. The magnitude of these four corrections amounted to only a few percent of the measured intensities.

IV. EXPERIMENTAL RESULTS WITH THE SIMPLIFIED POLARIMETER

The gamma-ray pulse-height spectra of Ce^{139} and Ce^{141} at $\theta=0$ deg and $\theta=90$ deg at a temperature of

[4] L. E. Glendenin, Anal. Chem. **27**, 50 (1955).

[5] H. Meyer, Phil. Mag. **2**, 521 (1957).

TABLE I. Nuclear reactions for producing Ce^{139} and Ce^{141}.

Product	Reaction	Target	Target thickness	Bombardment conditions
Ce^{139}	$La^{139}(p,n)Ce^{139}$	La metal (natural)	3 mils	ORNL 88-in. cyclotron, 8 h of 21-MeV protons at 200 μamp.
Ce^{141}	$Ce^{140}(n,\gamma)Ce^{141}$	Ce_2O_3 powder (natural)	100 mils	LRL, Livermore pool-type reactor, 16 h of thermal neutrons at 5×10^{13} n/cm^2/sec.

1.2°K and at 0.02°K are shown in Figs. 2 and 3, where θ is the angle between the NaI counter axis and the axis of orientation. The third line in each spectrum is for a point source of the isotope. Haag, Shirley, and Templeton[3] have measured as functions of temperature the angular distributions and the plane polarizations (using a standard polarimeter) of the 166-keV and the 142-keV gamma rays. They find the nuclear magnetic moment of Ce^{139} to be $|\mu_N|=0.95\pm0.20$ nm and the mixing ratio for the mixed $M1$, $E2$ 166-keV transition to be

$$\delta(E2/M1)=+0.034\pm0.034. \quad (1)$$

It was shown in Ref. 3 that for the spin sequence

$$\tfrac{3}{2} \xrightarrow{i_\beta=1} \tfrac{5}{2} \xrightarrow[166\text{ keV}]{M1,E2} \tfrac{7}{2},$$

the polarization p may be expressed as

$$p=\frac{1+0.7486B_2[(-\frac{1}{2})F_2'(1,\frac{7}{2},\frac{5}{2})+3F_2''(1,\frac{7}{2},\frac{5}{2})]}{1+0.7486B_2[(-\frac{1}{2})F_2'(1,\frac{7}{2},\frac{5}{2})-3F_2''(1,\frac{7}{2},\frac{5}{2})]}, \quad (2)$$

where the $k=4$ terms are exactly equal to zero. For Ce^{141} they find $|\mu_N|=1.30\pm0.20$ nm and the mixing ratio for the mixed $M1$, $E2$ 142-keV transition to be

$$\delta(E2/M1)=+0.066\pm0.022. \quad (3)$$

It was also shown in Ref. 3 that for the spin sequence

$$\tfrac{7}{2} \xrightarrow{i_\beta=0} \tfrac{7}{2} \xrightarrow[142\text{ keV}]{M1,E2} \tfrac{5}{2},$$

the polarization p becomes

$$p=\frac{1+B_2[(-\frac{1}{2})F_2'(1,\frac{5}{2},\frac{7}{2})+3F_2''(1,\frac{5}{2},\frac{7}{2})]}{1+B_2[(-\frac{1}{2})F_2'(1,\frac{5}{2},\frac{7}{2})-3F_2''(1,\frac{5}{2},\frac{7}{2})]}, \quad (4)$$

where the $k=4$ terms are approximately equal to zero. The value of B_2 at each temperature can be calculated using the measured $|\mu_N|$ and the $F_2'(L_nI_nI_{n-1})$ and $F_2''(L_nI_nI_{n-1})$ are functions only of the mixing ratio $\delta(E2/M1)$ and the spin sequence.

Using the new polarimeter, spectra such as shown in Figs. 2 and 3 were measured as functions of temperature simultaneously at $\theta=0$ deg and $\theta=90$ deg. The change of intensity with temperature of the spectra in the peak at 166 keV for Ce^{139} and at 142 keV for Ce^{141} agreed with the previously published results.[3] However, the intensities in the Compton region of the spectra displayed an entirely different relationship than did the peak intensities. Schooley *et al.*[6] have independently found this same effect and these results corroborate their interpretation of it.

It was noticed that an appropriate calculation based on the results of these spectra in the region between the two vertical lines in Figs. 2 and 3 yielded a value for the gamma-ray mixing ratio $\delta(E2/M1)$, without having recourse to a standard polarimeter measurement. This can be demonstrated as follows. A comparison of the geometry of the simplified polarimeter in Fig. 1 with that of a standard polarimeter reveals that the

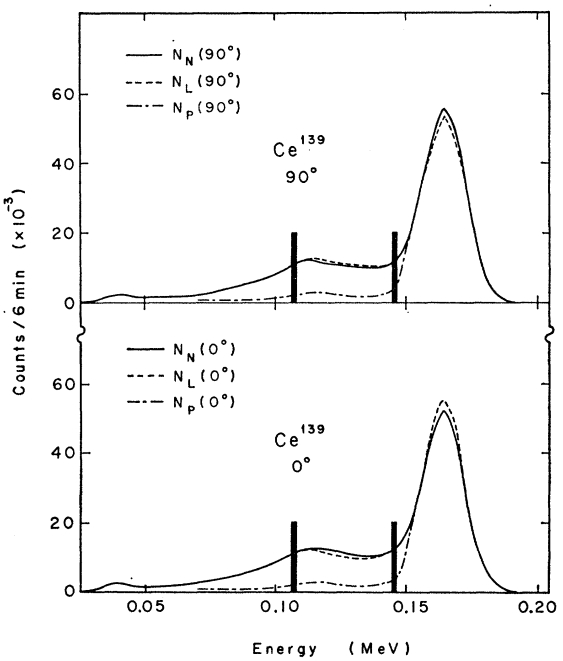

FIG. 2. Gamma-ray pulse-height spectra for Ce^{139} at 1.2°K (solid line) and at 0.02°K (dashed line) for $\theta=0$ deg and $\theta=90$ deg. The third line at $\theta=0$ deg and $\theta=90$ deg is the spectrum of a point source of Ce^{139}.

[6] J. F. Schooley, D. D. Hoppes, and A. T. Hirshfeld, J. Res. Natl. Bur. Std. **66A**, 317 (1962).

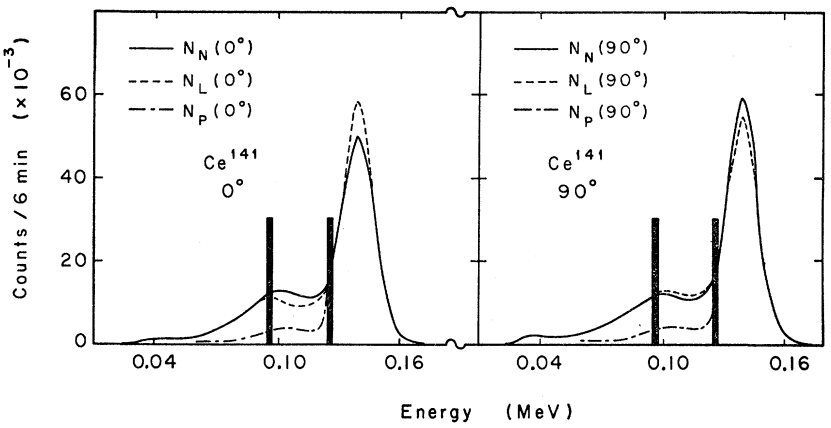

FIG. 3. Gamma-ray pulse-height spectra for Ce^{141} at 1.2°K (solid line) and at 0.02°K (dashed line) for $\theta=0$ deg and $\theta=90$ deg. The third line at $\theta=0$ deg and $\theta=90$ deg is the spectrum of a point source of Ce^{141}.

$N=N_{\parallel}/N_{\perp}$ measured with the standard polarimeter[3] whose scattering crystal is located at $\theta=90$ deg is equivalent to the $N=N_0/N_{90}$ measured with this simplified technique. Here, N_0 and N_{90} are, respectively, the "appropriate intensity" of quanta recorded in the $\theta=0$ deg and in the $\theta=90$ deg NaI counters. The phrase "appropriate intensity" can be made explicit with the equation

$$N=\frac{N_0}{N_{90}}=\left(\frac{N_L(0°)-I(0°)N_P(0°)}{N_N(0°)-N_P(0°)}\right)\times\left(\frac{N_L(90°)-I(90°)N_P(90°)}{N_N(90°)-N_P(90°)}\right)^{-1}, \quad (5)$$

where $N_L(\theta)$, $N_N(\theta)$ and $N_P(\theta)$ are the intensities of scattered gamma radiation recorded by the θ deg NaI counter with, respectively, the source crystal at a temperature lower than 1.2°K, the source crystal at the normalization temperature of 1.2°K, and the source crystal and its entire orientation system surroundings replaced by a point source of Ce^{139} or Ce^{141} of equal *peak* intensity at room temperature. The function $I(\theta)$ equals the intensity at a temperature T of the full energy gamma-ray *peak*, normalized to the intensity at 1.2°K, at which temperature $I(\theta)$ was found to be isotropic for both isotopes. For this particular polarimeter, Eq. (5) is an approximation since the measured N_{90} represented not only those quanta emitted at $\theta=90$ deg and scattered, but also those quanta emitted at all values of θ and scattered into the N_{90} counter.

Equation (5) is based on the fact that $N_N(\theta)-N_P(\theta)$ is the intensity of gamma radiation (unpolarized) Compton scattered by the source crystal and its copper, glass, and liquid helium and nitrogen surroundings and that $N_L(\theta)-I(\theta)N_P(\theta)$ is the intensity of gamma radiation (partially or totally polarized) preferentially Compton scattered by the source crystal and its surroundings. It is necessary to multiply $N_P(\theta)$ by the appropriate $I(\theta)$ in this expression to take account of the change in intensity of the spectrum due to the alignment of the nuclei at the low temperature. The $I(\theta)$ were calculated from the results of Haag, Shirley, and Templeton, the $N_P(\theta)$ were measured at room temperature and the $N_N(\theta)$ at 1.2°K for each of the two NaI counters in their experimental position at 10 cm from the source crystal, and of course, the $N_L(\theta)$ were measured as functions of temperature simultaneously at $\theta=0$ deg and $\theta=90$ deg.

The experimental results for N as a function of temperature for Ce^{139} and Ce^{141} are shown in Fig. 4. The horizontal rectangles and lines depict the change in $1/T$ during a measurement[3] of N for, respectively, Ce^{139} and Ce^{141}. The open circles and points are the results of this work for, respectively, Ce^{139} and Ce^{141}. The statistical errors of these measurements are denoted by the vertical lines. These errors were approximately the same for every point in each of the four sets shown. The consistency between the two techniques of measurement appears to be rather good.

It is now necessary to find the geometry correction quantity, defined as R, for the simplified polarimeter so that the experimental $N=N_0/N_{90}$ can be used to find the function p. A comparison of the $N=N_{\parallel}/N_{\perp}$

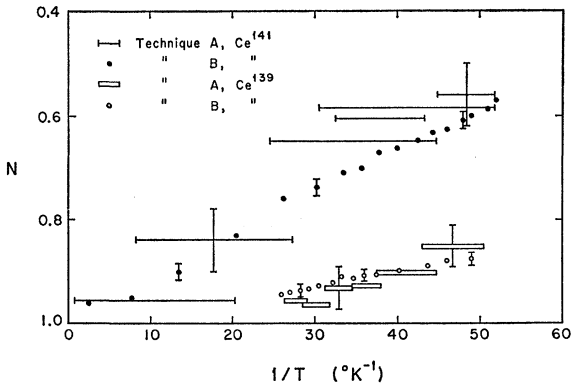

FIG. 4. Experimental values of N versus $1/T$. Technique A refers to the results obtained with the standard polarimeter. Technique B refers to the results obtained with the simplified polarimeter.

and $N=N_0/N_{90}$ of Fig. 4 shows that, to a reasonable approximation, R is the same for the two polarimeters. Thus, the standard polarimeter values for R, found by a calibration with Co^{60}, give $R=3.35\pm0.45$ for 166 keV and $R=3.45\pm0.45$ for 142 keV.

It is interesting to note that the average gamma-ray scattering angle δ is different for the two polarimeters and thus $\Delta\delta$ and $\Delta\eta$ (η is the angle between the direction of polarization of the incident quantum and the plane of scattering) are different, even though the two polarimeters have approximately the same R in *this* energy region. An average gamma-ray scattering angle of $\delta=80$ deg was utilized with the standard polarimeter, whereas geometrical considerations illustrated in Fig. 1 are consistent with the experimental results of Table II giving an average $\delta>90$ deg for the new polarimeter. Table II gives the experimental results on the percentage of Compton scattering caused by the various components of the orientation system, utilizing the 15-g neodymium ethylsulfate source crystal containing Ce^{139} nuclei in lattice sites. Table II shows that the Compton scattering is produced in various media at different distances from the source, but nevertheless, indicates by a geometrical calculation an average scattering angle of about $\delta=95$ deg. The function R is not very sensitive to small changes in this average scattering angle, thus this approximation is reasonable. Therefore, using $\delta=95$ deg and the value of R in this energy region for the standard polarimeter, one finds that $\Delta\delta=\Delta\eta=80\pm8$ deg for the new polarimeter, where the uncertainty in this angular spread comes from the uncertainty in R.

TABLE II. Compton scattering of the 166-keV gamma ray of Ce^{139}.

Scatterer	Radius (cm)	% of total scattering
Neodymium ethylsulfate crystal	1.2	24.8
Cryostat and two coils	1.5	24.7
Helium Dewar and liquid helium	2.5	29.6
Nitrogen Dewar and liquid nitrogen	3.8	20.9
		100.0

Consequently, for this simplified polarimeter, one takes the angular spread to be $\Delta\delta=\Delta\eta=80\pm8$ deg with $\delta=95$ deg. This spread in δ was utilized to locate the vertical lines in Figs. 2 and 3 and thus define the energy range of the scattered gamma rays utilized for the calculation of $N=N_0^\circ/N_{90^\circ}$ of Fig. 4. In evaluating the N from spectra such as those of Figs. 2 and 3, one experimental problem was discovered and a solution found. Sometimes, a slight shift in the electronic gain of the counting system in the time between a low temperature measurement of $N_L(\theta)$ and the 1.2°K normalization measurement of $N_N(\theta)$ was detected as leading to erroneous values for N. This was overcome by only utilizing the portion of the spectrum corresponding to $135^\circ>\delta>95^\circ$ in the calculation of N. This is justified in this case as, in the measurements where no electronic shift occurred, it was found that within experimental uncertainty, the portion of the spectrum corresponding to $135^\circ>\delta>55^\circ$ gives the same results for N as the portion corresponding to $135^\circ>\delta>95^\circ$, i.e., the preferential Compton scattering is, within experimental error, symmetric about $\delta=95$ deg for this polarimeter.

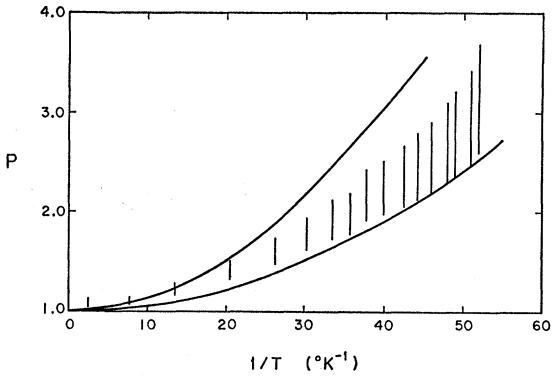

FIG. 5. Experimental results of p for Ce^{139} and the corresponding theoretical extremes for $+0.04>\delta(E2/M1)>-0.02$ and $1.15>|\mu_N|>0.75$ nm.

The values of p as a function of temperature for Ce^{139} and Ce^{141} are given in Figs. 5 and 6. For the 166-keV gamma ray of Ce^{139}, a value of $R=3.35\pm0.45$ was used with the experimental N to calculate p. For the 142-keV gamma ray of Ce^{141}, the value $R=3.45\pm0.45$ was used. The vertical lines in Figs. 5 and 6 represent both the uncertainty in R and the statistical error of the measurement of N. The statistical error contributes only about 20% to the total error shown, a gain of a factor of three over the standard polarimeter. The two solid lines in Fig. 5 represent for Ce^{139} the theoretical extremes calculated from Eq. (2) for $1.15>|\mu_N|>0.75$ nm and $+0.04>\delta(E2/M1)>-0.02$. The two lines of Fig. 6 represent for Ce^{141} the theoretical extremes calculated from Eq. (4) for $1.50>|\mu_N|>1.10$ nm and $+0.06>\delta(E2/M1)>-0.04$. The theoretical curve for any value of $|\mu_N|$ and $\delta(E2/M1)$ between these limits would fall between these curves. Thus a comparison of the value $\delta(E2/M1)=+0.01\pm0.03$ for the 166-keV gamma ray of Ce^{139} with the value given in Eq. (1) and a comparison of the value $\delta(E2/M1)=+0.01\pm0.05$ for the 142-keV gamma ray of Ce^{141} with the value given in Eq. (3) and with the value of $\delta(E2/M1)=+0.068\pm0.008$ of Schooley *et al.*[6] indicates that the results obtained by the two methods are not inconsistent. Two needed improvements can be applied to this simplified polarimeter so that the experimental errors are substantially reduced below those of the errors for a standard polarimeter. The first is to use a direct calibration technique to obtain R, rather than the double calibration technique used in this paper. Depending on the particular substance utilized as the source

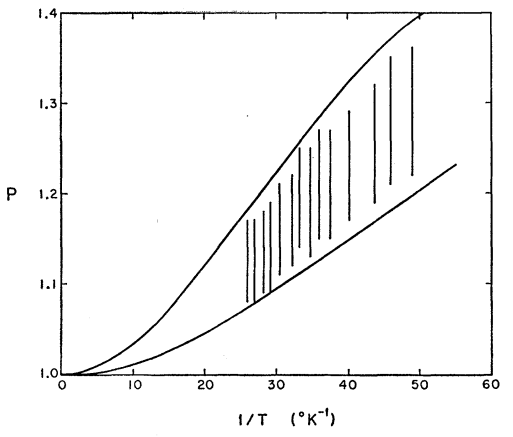

FIG. 6. Experimental results of p for Ce^{141} and the corresponding theoretical extremes for $+0.06>\delta(E2/M1)>-0.04$ and $1.50>|\mu_N|>1.10$ nm.

crystal, one could grow into this crystal nuclei of known magnetic moments and spins whose gamma transition is either pure or whose mixing ratio has been accurately determined and thus measured directly the angular spread of δ and η, and thereby determine R as a function of energy. Of course, the choice of an isotope for this purpose must take into account that the nucleus chosen must be capable of being oriented in the crystal at low temperatures.

The second improvement is to utilize either two wedge-shaped scatterers placed directly above and below the source crystal or a ring-shaped scatterer of appropriate length and thickness placed closely around the source crystal with its axis parallel to the orientation axis. This ring-shaped scatterer has been incorporated into a polarimeter constructed by Brimhall and Page.[7] Their polarimeter achieves a high detection efficiency, accepting gamma radiation over all azimuthal angles and also a range in θ, by use of a Lucite or aluminum scatterer in the form of a shell of revolution. For low-temperature nuclear orientation experiments the scatterer should be constructed of say, glass or Lucite, so that it would not interfere with the mutual susceptibility measurements. As now constructed each of the two NaI counters in this simplified polarimeter sees a different geometry as the Dewar system possesses cylindrical rather than spherical symmetry. Thus an error is introduced into the measurements both because R is different for each of the two NaI counters and because as previously noted, the N_{90} counter records scattered gamma rays not only at $\theta=90°$, but at all values of θ. These two sources of error were taken into consideration in this work by using an average geometry factor R in the calculations.

It has been demonstrated in theory and in practice that this new type of polarimeter can be successfully utilized to measure the plane polarization of gamma radiation in low-temperature nuclear orientation experiments. In addition, under equivalent conditions, the intensity of radiation preferentially scattered and analyzed by this new polarimeter is from 10 to 25 times greater than that for a standard polarimeter. Consequently, the statistical error is from $\frac{1}{3}$ to $\frac{1}{5}$ that of the standard polarimeter. The reason for this difference in intensities is that a standard polarimeter scattering crystal accepts only direct gamma radiation emitted in the narrow cone defined by the lead shield which protects the two NaI counters from direct radiation, while the new polarimeter utilizes the gamma radiation emitted in all 360 deg of a plane.

One might remark that utilizing this new technique facilitates carrying out a double scattering experiment on plane-polarized gamma radiation, where the first scattering would take place in the source crystal and its ring-shaped scatterer and the second in the scattering crystal of a standard polarimeter. At present, it is not clear that this type of experiment would yield any new results, since the polarization of the quanta is vectorial rather than tensorial, and all plane-polarization components are determined in a single-scattering experiment.

Finally, this technique of scattering the quanta in the source crystal to analyze their polarization might be utilized to measure the circular polarization of quanta in low-temperature nuclear-polarization experiments, where the nuclei are polarized rather than simply aligned. If so, it would greatly simplify the experimental apparatus required for these experiments.

ACKNOWLEDGMENTS

I wish to thank Professor David A. Shirley for his many suggestions and for his insistence that one should always utilize two gamma-ray counters in low-temperature orientation experiments. I gratefully acknowledge the ability of Mitch Nakamura in the field of electronics.

[7] J. E. Brimhall and L. A. Page, Bull. Am. Phys. Soc. 7, 9 (1962).