the fourfold axis, z, is the direction of the applied field. The phonon generated in the scattering process propagates along the x axis, and may be (1) transversely polarized in the z direction, giving Raman-tensor elements α_{zz}, and $\alpha_{xx}=\alpha_{yy}$; (2) transversely polarized in the y direction, giving Raman-tensor elements $\alpha_{yz}=\alpha_{zy}$; or (3) longitudinally polarized, giving Raman-tensor elements $\alpha_{xz}=\alpha_{zx}$. We have observed α_{zz} and α_{zy} for the two degenerate low-frequency transverse phonons, and find $|\alpha_{zz}|^2 \cong 5|\alpha_{zy}|^2$; and $|\alpha_{xx}=\alpha_{yy}|^2 \approx 0$.

Finally, we mention the observation of some polarization saturation effects on the Raman scattering at low temperatures and high fields. Wemple[3] and Kahng and Wemple[7] have observed that the low-frequency polarization in $KTaO_3$ is not strictly proportional to applied field, but tends to saturate, the fields necessary for appreciable saturation being lower, the lower the temperature. Since ϵ_0 is so intimately connected with the frequency of the phonon studied here [see Eq. (2)], one expects high applied fields to affect the phonon and thus the spectrum of light scattered from it. We have observed such effects at low temperatures (8°K) and for fields in the range of 1000 to 10 000 V/cm. While these observations are preliminary, it is clear that the mode frequency shifts to higher values as the field is increased, and there appears to be a change in the line shape of the scattered light. However, our present field-modulation scheme is inappropriate for the detailed study of such effects and further work is being done with a modified apparatus.

We have shown that it is experimentally possible to study phonons which are not naturally Raman active with the help of external electric fields. This technique is capable of finer detail than IR reflectivity or neutron scattering in certain frequency ranges. The particular type of mode studied here can probably also be studied in several other paraelectric crystals, such as $SrTiO_3$ and $BaTiO_3$, for example. There the method should help resolve the question of possible anomalous first-order Raman lines recently reported for conventional Raman studies in these materials.[9]

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SCATTERING OF FAST ELECTRONS BY ORIENTED Ho^{165} NUCLEI*

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Many spherically symmetric nuclei have been investigated by the method of fast-electron scattering at Stanford in recent years.[1] A useful factor in determining the size of these nuclei is the well-pronounced diffraction structure of the measured differential scattering cross sections. However, nuclei with a large deformation do not exhibit such well-defined diffraction features and in such cases the accurate determination of the nuclear charge distribution is considerably more difficult.[2] Consideration was given to the possibility of obtaining more information about the deformed nuclei group by measuring the electron scattering cross sections for oriented nuclei.

The first experiment of this type was performed at Stanford University using the Mark III electron linear accelerator. The nucleus chosen for this experiment was Ho^{165} which has a large intrinsic electric quadrupole moment[3,4] of about

7.6 ± 1.5 b. Holmium metal has an antiferromagnetic helical structure below 20°K.[5] By application of a magnetic field in the basal plane perpendicular to the axis of hexagonal symmetry, it is possible to form a ferromagnetic structure. The direction of easy magnetization is the crystallographic direction $\langle 10\bar{1}0 \rangle$.[6] Our target was in the shape of a thin plate 0.83 mm thick, and was cut from a single crystal in such a way that the direction of easy magnetization was in the plane of the plate.

It is known from low-temperature specific-heat measurements on holmium metal[7] that, because of unpaired $4f$ electrons, there is an effective magnetic field of 7.6 MG acting at the site of the nucleus. This strong magnetic field enables one to achieve a high degree of nuclear orientation at the temperatures of liquid He^3. This fact was utilized in designing the target apparatus for the experiment.

The low-temperature apparatus is shown schematically in Fig. 1 and consisted of the usual nitrogen [No. 5 in the figure], liquid-helium [6], and pumped liquid-helium [7] baths. The target sample [9] was placed directly in the liquid-He^3 bath [8] in a flat chamber with

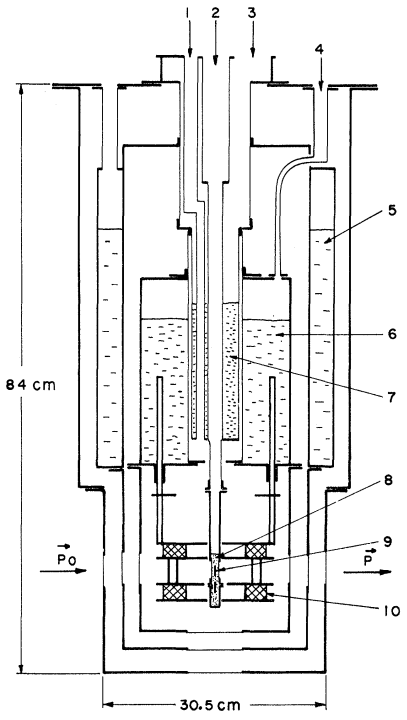

FIG. 1. Cryogenic apparatus used for aligning the Ho^{165} nuclei.

stainless steel windows of 0.025 mm thickness at each end. The aluminum windows in the helium 4.2°K radiation shield were 0.025 mm thick, in the nitrogen shield 0.006 mm thick, and in the outer shield 0.05 mm thick. The sample was located in a magnetic field produced by a pair of superconducting Helmholtz coils [10] which were cooled by conduction from the liquid He^4 4.2°K bath. The magnetic field used was about 4 kG which produced approximately 92% of the saturation megnetization in the single-crystal target, and about 20% magnetization in a polycrystalline target whose dimensions were similar to the single-crystal target.

The lowest temperature that could be achieved when the electron beam was incident upon the Ho target was 0.35°K; at this temperature the alignment in the single-crystal sample was approximately 45%. In order to avoid excessive heating in the cold target, the incident beam intensity was reduced 4 orders of magnitude from the maximum available.

The energy of the incident electron was 200 MeV. The scattered electrons were detected by a 100-channel scintillation ladder[8] located in the image plane of a 72-in. double focusing iron spectrometer.[9]

The collective nuclear model of Bohr and Mottelson[10] for highly deformed nuclei such as holmium predicts low-lying excited states which correspond to a collective rotation of outer nucleons. These levels are excited with energies less than 0.3 MeV.[11] The momentum resolution of the detecting system did not allow a separation to be made between the inelastically scattered electrons which excited these states and the elastically scattered electrons. The experimental and theoretical cross sections presented will therefore include contributions from both elastic and inelastic scattering.

In order to reduce the effect of various fluctuations and drifts in the accelerator and counting system, a sample of polycrystalline Ho was used for comparison purposes. This sample was frequently alternated in position with the single-crystal sample. The alignment for the polycrystalline target was less than 10%. The observed change in cross section between aligned and nonaligned Ho^{165} was then calculated from the ratio of the data obtained from the two samples.

In Fig. 2 the results obtained for the cross sections for randomly aligned Ho nuclei are shown. The experimental points were taken

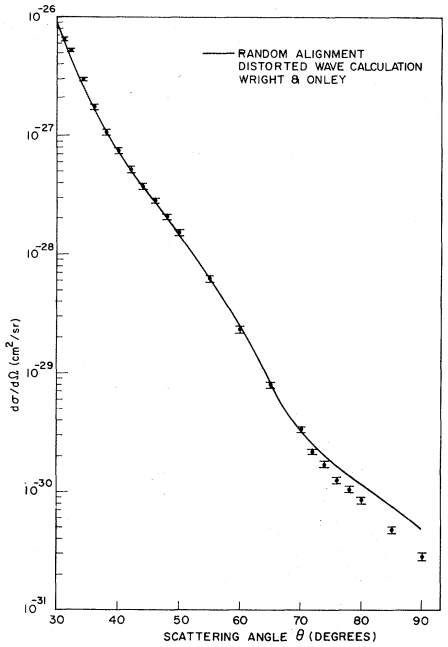

FIG. 2. Ho^{165} random-alignment scattering cross section.

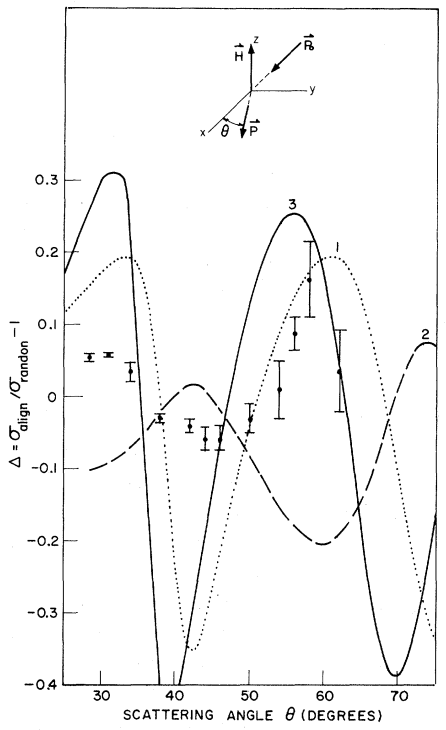

FIG. 3. Experimental alignment effect on Ho^{165} with alignment parameter $f_2 = 45\%$. Theoretical curves are calculated for $f_2 = 50\%$.

with a thin foil of Ho, 0.102 mm thick.[12] The cross sections were found in the usual way by measuring the area under the elastic (plus inelastic) peak after corrections for variations in counter efficiencies and radiative effects.[13] The theoretical curve shown was calculated by Wright and Onley[14] assuming a Bohr-Mottelson representation of the nucleus. The nuclear charge distribution is assumed to consist of a spherical plus quadrupole term. The spherical component is treated using a phase shift analysis while the quadrupole interaction is approximated to first order using the distorted-wave method for electrons. A spherical Fermi distribution was used, with $\rho_0(r) = 1/\{1 + \exp[(r-C_0)/z_1]\}$, where $C_0 = 6.18$ fm and $z_1 = 0.57$ fm. The intrinsic quadrupole moment was chosen to be $Q_0 = 8\times10^{-24}$ cm^2.

To investigate the effect of alignment on the cross sections, let us define $\Delta = \sigma_A/\sigma_N - 1$, where σ_A is the cross section for aligned nuclei in the cold sample and σ_N is the cross section for randomly oriented nuclei. The results of the present experiment for one particular orientation where the direction of alignment is perpendicular to the scattering plane are shown in Fig. 3. The theoretical curves shown in the figure are calculated for 200-MeV incident electron energy and a value of 50% for the alignment parameter. Curve 1 represents a Born approximation calculation.[15] The nucleus is assumed to be uniformly charged ellipsoid of revolution with $Q_0 = 8.56\times10^{-24}$ cm^2 and for which the radius of an equivalent sphere is 6.58 fm. Curve 3 is calculated using the Schiff approximation for the same choice of nuclear parameters. This latter method should only be valid for scattering angles much larger than 22°. Curve 2 is another result obtained by Wright and Onley assuming the same charge distribution as previously described.

It is possible to obtain a reasonable fit to the experimental points for the randomly aligned cross section (Fig. 2). A significant deviation from the predicted theoretical curve occurs only for scattering angles $\theta > 70°$. The determination of the nuclear charge parameters from these experimental data depends upon the model assumed for the charge distribution and also the validity of using the Bohr-Mottelson description of the Ho nucleus.

The experimental results of the aligned cross sections are not in agreement with any of the theories. One has to expect this in the Born

approximation (curve 1, Fig. 3), which cannot be valid for a heavy nucleus such as Ho. The calculation based on the Schiff approximation (curve 3) is not expected to be accurate for small angles. At larger angles it predicts the positions of the zeros, minima and maxima with a fair degree of accuracy. The magnitude of the measured effect is very close to that calculated in the distorted-wave treatment of Wright and Onley (curve 2) for a nucleus with a smooth edge. However, there is no agreement with regard to the location of maxima and minima.

The monopole and quadrupole interference terms that arise in the theoretical calculations with nonzero alignment must, due to experimental limitations, include the excitation of the nuclear rotational levels. The approximations and difficulties involved in including these inelastic amplitude terms are thought to be the primary reason for the disagreement between this theory and the experimental results.

It is clear from the results that experiments involving electron scattering from oriented nuclei are far more sensitive to small changes in the parameters describing the nuclear charge-density distribution than is the case with measurements on randomly oriented nuclei. With the development of better theoretical treatment and the extension of these measurements to different relative orientations of the spin axis and the scattering plane, it will probably be possible to attain a nearly model-independent value for the static quadrupole moment.[16] The preparations to extend this type of measurement are in progress.

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