Elastic Scattering of 5-10-MeV Protons from Aligned ^{165}Ho†

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The scattering of protons from an aligned ^{165}Ho target $[B_2/B_2(\max) = -0.34]$ is analyzed to obtain an estimate of the nuclear quadrupole moment or, equivalently, the nuclear deformation parameter β. The data are in resonable agreement with the result $\beta = 0.33$ derived from Coulomb excitation measurements.

We have measured the cross section for the scattering of 5–10-MeV protons from a target of ^{165}Ho having a nuclear alignment $B_2/B_2(\max) = -0.34$. In addition to providing a measurement of the nuclear quadrupole moment of ^{165}Ho, the experiment demonstrates that the effect of local heating from a charged-particle beam does not represent an insurmountable difficulty. The way is thus opened for future experiments involving both polarized targets and polarized beams.

The scattering of charged particles from an aligned target at energies well below the Coulomb barrier was suggested several years ago as a technique for the measurement of nuclear quadrupole moments.[1] In the WKB or semiclassical approximation, the 180° scattering cross section is given by[2]

$$\sigma(180°) \approx \sigma_R(1 - 3.2\langle Q\rangle/2Za^2), \qquad (1)$$

where σ_R is the Rutherford cross section, Z is the atomic number of the target nucleus, a is the classical distance of closest approach, and $\langle Q\rangle$ is the expectation value of the quadrupole-moment operator. Since $\langle Q\rangle$ is proportional to the product of the nuclear alignment and the intrinsic quadrupole moment Q_0, it is possible to determine Q_0 by comparing the scattering from an aligned and an unaligned target. Although technically more difficult than the usual procedures for the measurement of quadrupole moments, this approach has the advantage that the extraction of the quadrupole moment from the data is almost model independent. The only requirement is a knowledge of the electromagnetic interaction at nonrelativistic velocities.

In the present experiment, nuclear alignment was achieved by cooling holmium metal in the form of a single crystal to 0.210°K using a ^{3}He-^{4}He dilution refrigerator. The cryostat[3] and dilution refrigerator were similar in design to the system used in the construction of a polarized ^{59}Co target which has been described previously.[4] The operating temperature of the refrigerator, in the absence of an external heat load, was below 0.030°K.

The experimental arrangement is shown schematically in Fig. 1. At a distance of 2 m from the target, a 10-nA proton beam from Stanford University's model FN tandem accelerator was passed through a gold foil 0.0005 cm thick ($F3$ in Fig. 1), which resulted in a uniform and stable beam intensity at the target of approximately 10 pA/cm^2. The beam entered the cold section of the cryostat through a 0.0005-cm Havar foil window ($F1$ in Fig. 1) and was subsequently collimat-

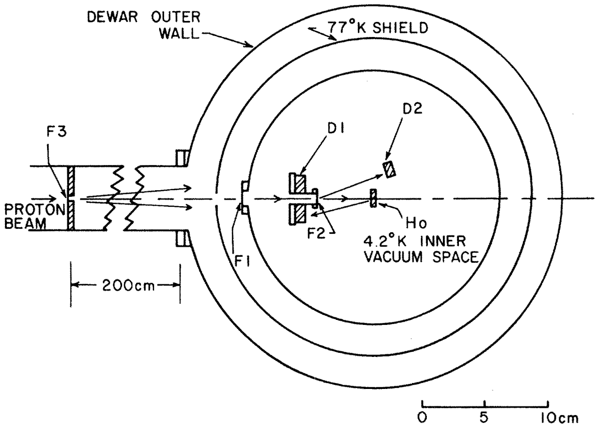

FIG. 1. Schematic diagram of the experimental arrangement, cross-sectional view, as seen from below. The inner vacuum space which houses the detectors, target, and dilution refrigerator is isolated from the accelerator vacuum by the 0.0005-cm Havar foil $F1$. The function of the 0.0005-cm gold foils $F2$ and $F3$ is described in the text. $D1$ is a silicon surface-barrier ring detector with a depletion depth of 0.8 mm; $D2$ is a surface-barrier detector with a depletion depth of 1 mm. Ho is the holmium crystal; the dilution refrigerator is not shown.

ed to 0.31 cm diam by a stainless-steel aperture which also served as a shield for the silicon surface barrier ring detector (*D*1 in Fig. 1). The protons backscattered from the holmium target were detected at an average angle of 174°. An additional gold foil 0.0005 cm thick (*F*2 in Fig. 1) covered the stainless-steel aperture, and protons scattered by this foil into a second silicon surface-barrier detector (*D*2 in Fig. 1) were used to monitor the beam intensity. The detectors were operated at a temperature of 20°K, where the resolution was comparable to that at room temperature. Typical spectra recorded by the two detectors at 10 MeV incident proton energy are shown in Fig. 2.

The use of a thick target was dictated by considerations of heat removal. The target was soldered to the copper bottom of the mixing chamber using Cd-Bi solder with the *c* axis of the crystal oriented along the direction of the proton beam. The surface was ground until the crystal was approximately 0.025 cm thick, polished to a 1-μm finish, and finally etched with a 1% solution of nitric acid until a satisfactory x-ray diffraction pattern was obtained.

The temperature of the dilution refrigerator mixing chamber was measured with a calibrated Speer carbon resistor, grade 1002.[5] During the actual running, the operating temperature of the mixing chamber was 0.180 ± 0.030°K with most of the heat load arising from the 20°K thermal radiation from the detectors. The average beam current was approximately 1 pA, and the temperature difference between the target surface and the dilution refrigerator was estimated to be 0.030°K based on measurements of the thermal conductivity of Cd-Bi solder junctions at low temperatures.[6] The final value adopted for the temperature of the holmium target was 0.210 ± 0.045°K.

It is well known that the crystal structure of holmium results in nuclear alignment at low temperatures even in the absence of an external magnetic field.[7] In the present experiment, the nuclear orientation at 0.210 ± 0.045°K is described by the following set of population parameters if the *z* axis is chosen coincident with the *c* axis of the crystal: $P_{\pm 7/2} = 0.034$, $P_{\pm 5/2} = 0.095$, $P_{\pm 3/2} = 0.165$, and $P_{\pm 1/2} = 0.206$. The corresponding nuclear alignment is $B_2/B_2(\max) = -0.34 \pm 0.04$, and the expectation value of the quadrupole moment operator is negative.

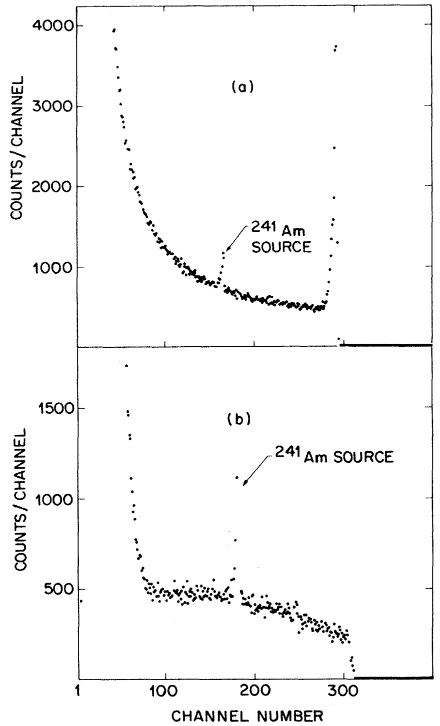

FIG. 2. (a) Spectrum of 10-MeV protons elastically scattered by foil *F*2 in Fig. 1 and detected by detector *D*2. The detector temperature is 20°K. The peak in the spectrum was used to monitor the beam intensity. The ^{241}Am source line was included in the spectrum to check the detector stability. (b) Spectrum of 10-MeV protons backscattered from the holmium target and detected by *D*1 in Fig. 1. The detector temperature is 20°K. The ^{241}Am source line was included in the spectrum to monitor the detector stability.

The quantity actually measured experimentally was the percentage change in cross section which occurred when the target was warmed from 0.21 to 1°K [at 1°K $B_2/B_2(\max) = -0.06$]. This change in cross section may be written as

$$\frac{\sigma_{0.21^\circ\mathrm{K}} - \sigma_{1^\circ\mathrm{K}}}{\sigma} = \frac{\Delta\sigma}{\sigma} = \frac{0.13_{1/2} + 0.07\sigma_{3/2} - 0.05\sigma_{5/2} - 0.15\sigma_{7/2}}{\sigma}, \tag{2}$$

where σ is the cross section for an unpolarized target and σ_m is the cross section for nuclei in magnetic substate *m*. Several cycles of "warm" and "cold" runs were taken at an incident proton energy of 10 MeV and also at an incident proton energy of 7.6 MeV. The spectrum of Fig. 2(b) was divided into bins corresponding to scattering events occurring within energy intervals of 500 keV width, and the quantity $\Delta\sigma/\sigma$ was ex-

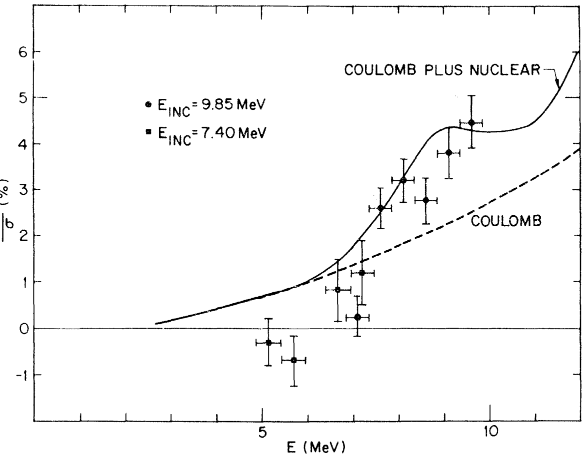

FIG. 3. $\Delta\sigma/\sigma$ as a function of energy. The solid curve is the result of the adiabatic coupled-channel calculation. The dotted curve is the WKB result of Ref. 2 which does not include the effect of the nuclear potential or inelastic scattering.

tracted for each bin. The results are presented in Fig. 3; vertical bars denote statistical uncertainties and horizontal bars denote the width of the energy bins.

The WKB calculation of Ref. 2, indicated by the dotted curve in Fig. 3, is adequate for the interpretation of the data at energies where the particle trajectory remains well outside the range of the nuclear potential. This condition is fulfilled at 5 MeV. At 10 MeV, however, the effect of the nuclear potential must be included and some form of coupled-channels calculation is required. The solid curve in Fig. 3 was calculated with the adiabatic coupled-channels code written by Barrett.[8] This code does not include a spin-orbit potential. Otherwise, the optical parameters employed by Tamura[9] in fitting the scattering of 17-MeV protons from ^{165}Ho were used. The value $\beta = 0.33$ ($Q_0 = 7.9$ b) for the nuclear deformation was taken from Coulomb excitation measurements.[10] The calculated curve of Fig. 3 includes a small contribution from inelastic scattering, which was not resolved experimentally from the elastic scattering.

In view of the technical difficulties involved in the experiment, the agreement between the calculated curve and the experimental data of Fig. 3 is considered satisfactory at this time. The three points which show poorest agreement with the calculated curve are obtained from energy bins in the low-energy part of the proton spectrum where multiple scattering and straggling may affect the analysis. Although a slight reduction in β would result in a better fit, further checks should be made of the nuclear alignment before concluding that such a reduction is necessary. For example, if the Cd-Bi solder junction were of poor quality, or if some appreciable percentage of the target surface were polycrystalline, the nuclear alignment might be significantly less than estimated.

In future experiments, the cryostat will be designed so that the detectors can be operated at liquid-nitrogen temperature. We hope to obtain greater precision in the measurements and to extend the energy range up to 15 MeV where the calculation indicates that $\Delta\sigma/\sigma$ should be 0.16. This should make it easier to perform experimental checks of the nuclear alignment (e.g., by measuring $\Delta\sigma/\sigma$ as a function of beam current). Similar experiments with α particles should also be of interest. From accurate measurements of $\Delta\sigma/\sigma$, it should be possible to obtain information on the shape of the nuclear quadrupole potential as well as the value of the quadrupole moment. A more complete description of the present experimental results is being prepared for publication elsewhere.

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