suggestions and for noting the possible relevance of the Bean and Livingston theory and also R. R. Hake for helpful comments. We are indebted to C. P. Bean and J. D. Livingston for making available the results of their theoretical investigation prior to publication. We wish to thank R. R. Hargrove for aid with specimen preparation, R. E. Gile for help with the measurements, and E. P. Parry for the chemical analyses.

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*Work supported in part by the U. S. Atomic Energy Commission.

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POLARIZATION IN THE ELASTIC SCATTERING OF 22-MeV PROTONS FROM DEUTERONS*

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The measurement and interpretation of the polarization in the scattering of low-energy nucleons by deuterons should have an important bearing on the understanding of nucleon-nucleon interactions in nuclear matter. Even though the two-body interaction may not be completely known, one would hope to predict the results of nucleon-deuteron scattering in terms of measured nucleon-nucleon scattering parameters, and to determine whether or not any specifically three-body interaction would be required to explain the results. Unfortunately, at low energies, where the results are of greatest interest with respect to their bearing on nuclear structure, the interactions among the three particles during the scattering are roughly equally strong, and thus the analytic solution of the problem becomes difficult. The maximum polarization is known to be small in p-p scattering ($<1\%$)[1,2] and in n-p scattering ($\approx 5\%$)[3,4] near 20-MeV bombarding energy. On the other hand, the polarization in the scattering of protons from complex nuclei reaches values of up to 100% at energies as low as 6 MeV. In scattering from the lightest nuclei, in particular, the maximum polarization is approximately 100% in p-^{4}He scattering at 6 to 14.5 MeV,[5,6] and about 55% in p-^{3}H and p-^{3}He scattering at 14.5 MeV.[6] The former is understandable in terms of the splitting of the $j=l+1/2$ and $j=l-1/2$ phase shifts due to the strong spin-orbit forces acting in the p-^{4}He (^{5}Li) system. Such an explanation might be considered for the p-^{3}H and p-^{3}He results, treating the target as a spin-zero nucleus and thereby ignoring any tensor interaction. However, an extension of this argument to the p-d system does not seem warranted since measurements of the polarization in p-d scattering have been consistent with zero or very small values at energies below 17 MeV.[7] Thus, determinations of polarization in p-d or n-d scattering at energies below 50 MeV should provide information useful to the understanding of this remarkable difference between the polarization induced in nucleon-nucleon scattering and that resulting from the scattering of the nucleon from a few-nucleon system.

A general theory of nucleon-deuteron scattering, including tensor forces but neglecting the distortion of the deuteron, has been developed,[8] but calculations based on this formalism are not presently available. An approximate calculation has been made which includes, also, the effect of deuteron distortion in n-d scattering below 3.5 MeV.[9] This calculation predicts a rapid variation of the neutron polarization with energy at 90° c.m., reaching a maximum of 12% near 1 MeV. Experimental results to date are not in agreement with respect to confirmation of this prediction.[10] Previous calculations[11] carried out for central forces alone had compared well with differential cross-section data up to 10 MeV but could not result in any nucleon polarization. At higher energies calculations employing the impulse approximation have had some success in fitting p-d polarization results at 150 MeV, and these calculations have been extended to energies as low as 40 MeV.[12]

We have measured in a double scattering experiment the proton polarization produced in the elastic scattering of 22-MeV protons by deuterons. Polarized protons were produced as recoil protons (at 130° c.m.) in the scattering of 45-MeV alpha particles in hydrogen using the alpha particle beam from the 60-inch Crocker cyclotron. The protons produced in this manner are approximately 100% polarized. The polarized proton beam entered a second scattering chamber containing deuterium at approximately 165 lb/in^2. A scattered proton or recoil deuteron produced by scattering in the second chamber was detected by one of two counter telescopes placed symmetrically on opposite sides of the polarized beam. The dE/dx of a particle was determined by the pulse height produced in a thin (0.006-in. to 0.023-in.) plastic scintillator and the energy (E) was determined from the pulse obtained by stopping the particle in a CsI crystal. A coincidence between dE/dx and E pulses was required to gate a multichannel analyzer which recorded and stored the spectrum of E pulses.

The primary alpha-particle beam intensity ranged up to about $2\frac{1}{2}$ μA. The laboratory energy of the polarized proton beam was 22 ± 1 MeV with principal contributions to the spread arising from the energy spread in the primary beam and by the angular acceptance of the collimating system defining the first scattering. The intensity of the polarized proton beam was about 6×10^6 particles/second. The angular resolution of the counters observing the second scattering was $\pm 4°$ at half-maximum with a roughly triangular resolution function. The counting rate after the second scattering was of the order of one count per second (in the elastic-scattering peak) in the forward hemisphere. A sample of data taken at a forward angle is shown in Fig. 1. Background under the elastic-scattering peak, in this case less than 1% of the number in the peak, has been subtracted. The spectrum consists of a main peak of elastically scattered protons and a continuum of protons at lower energies arising from

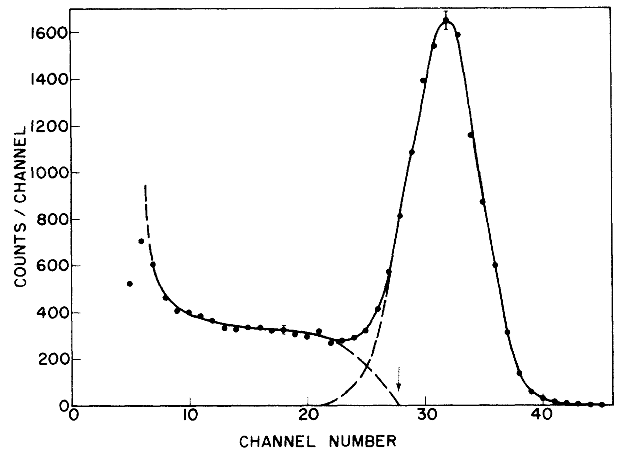

FIG. 1. Pulse-height spectrum obtained from a counter telescope placed at an angle of 40° (left) from the beam direction. The spectrum consists of a peak of 17.3-MeV elastically scattered protons and a continuum at lower energies. The arrow indicates the calculated end point of the continuum. Standard deviations due to counting statistics are indicated on two of the points.

the breakup of a deuteron by an incident proton. At some angles a peak of elastically recoiling deuterons is seen superimposed on the continuum.

At proton-scattering angles greater than 106° (c.m.) it became easier to measure the associated forward-recoiling deuterons than the backward-scattered protons because of the low energies of protons scattered at large angles. For this measurement, in order to enhance the separation of deuteron pulses from proton pulses, the CsI scintillator was made just thick enough to stop the deuterons while the scattered protons at the same angle passed through the scintillator losing only a fraction of their energy.

The method of analysis of the data is partially indicated in Fig. 1. The three-body breakup continuum was extrapolated to its calculated endpoint and subtracted from the elastic-scattering peak. A statistical error was computed based on the number of counts in the peak, the subtraction of background, and an estimate of the error involved in the extrapolation and subtraction of the continuum spectrum. The right and left counters were interchanged for about half of the time spent in determining each point in order to minimize systematic errors and to correct for differences in counter efficiency and geometry. The zero of the angular scale and corrections for the misalignment of the principal collimators in the counters were determined by passing the counters through the polarized beam at reduced beam intensity. This procedure corrects to first order for angular errors arising from misalignment of the beam in the second scattering chamber.

The polarization was determined from the right-left asymmetry in the second scattering. The sign of the polarization is given according to the Basle convention (positive polarization in the direction $\vec{k}_{inc}\times\vec{k}_{scat}$). For elastic scattering the asymmetry is given by $P_1P_2(\theta)$, where P_1 is the fractional polarization of the proton beam and $P_2(\theta)$ is the proton polarization that would be induced in the scattering of unpolarized protons by deuterons. We have assumed P_1 to be 1.0 and thus $P_2(\theta)$ to be equal to the asymmetry.[2]

The results are presented in Fig. 2 and Table I. The error associated with each point is the statistical error mentioned above. Most systematic errors would merely shift the zero of the polarization scale and it is believed that effect of all systematic errors is less than ±2%. The results show a substantial polarization in p-d scattering at 22 MeV. The large values reached by the polarization suggest that it may be difficult to explain the results in terms of nucleon-nucleon scattering parameters even with maximum constructive interference in the scattering of the incident proton from the two particles of the deuteron.

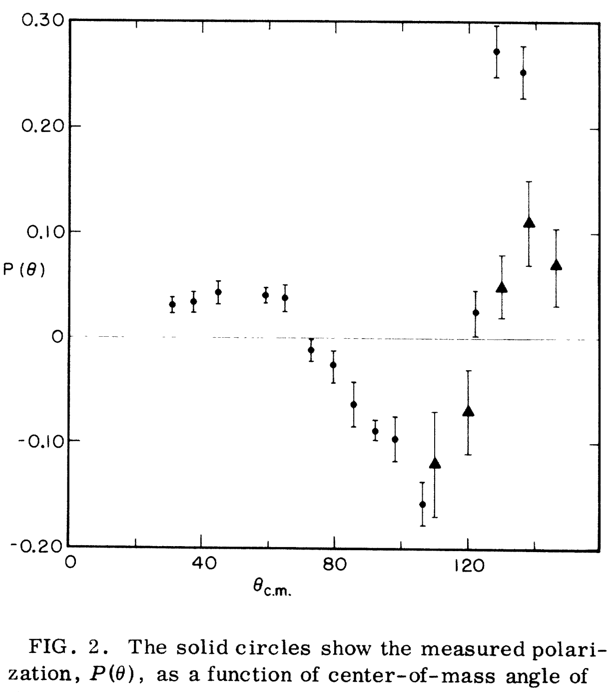

FIG. 2. The solid circles show the measured polarization, $P(\theta)$, as a function of center-of-mass angle of the scattered protons. See text for discussion of indicated errors. The triangular points are the n-d data of reference 13 for comparison.

Table I. Measured polarization, $P(\theta)$, at various center-of-mass scattering angles in the elastic scattering of 22-MeV protons by deuterons.

$\theta_{c.m.}$ (degrees)	$P(\theta)$
31.4	+0.030 ±0.007
37.2	+0.033 ±0.010
44.5	+0.042 ±0.011
58.8	+0.039 ±0.007
64.4	+0.037 ±0.013
72.5	-0.012 ±0.010
79.2	-0.027 ±0.016
85.7	-0.076 ±0.021
92.0	-0.088 ±0.010
98.0	-0.096 ±0.021
106.2	-0.157 ±0.021
122.0	+0.023 ±0.022
128.0	+0.271 ±0.023
136.0	+0.253 ±0.025

Also shown in Fig. 2 are the somewhat smaller back-angle values of $P(\theta)$ in n-d scattering, determined recently at 23.7 MeV.[13] That experiment utilized, from the $T(d,n)^4He$ reaction, a beam of neutrons whose polarization was taken to be $P_1 = 0.60$, the value of the proton polarization from the mirror reaction $^3He(d,p)^4He$.[14] Values for the neutron polarization, which range from 0.46[3] to 0.64,[15] are less precise because of uncertainties in the analyzing power of the helium analyzer used. Thus, if a smaller value of P_1 had been taken, larger values of $P(\theta)$ in n-d scattering would have resulted. More precise data on both systems will be required before any significant back-angle difference between the p-d and n-d results can be claimed.

*This work was supported in part by the U. S. Atomic Energy Commission.

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PROPERTIES OF HIGH-SPIN ROTATIONAL STATES IN NUCLEI*

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It is well established that nuclei in the region $150 < A < 190$ have sizable prolate-spheroidal deformations, and consequently have well-defined rotational bands built on the various intrinsic levels. In the present work rather high-lying members of the ground-state rotational bands of a number of even-even nuclei in this region have been studied following heavy ion reactions of the type ^{165}Ho(^{11}B, $4n$)^{172}Hf. Odd-proton-number targets (^{159}Tb, ^{165}Ho, and ^{169}Tm) and projectiles (^{11}B, ^{14}N, and ^{19}F) have been used to produce ^{166}Yb, ^{166,168,170,172}Hf, and ^{172,174,176}W. The bombarding energy has been adjusted in each case to give predominantly the particular even-even nucleus desired. We have studied the conversion electron and gamma-ray spectra from such targets during the 3-msec beam burst of the Hilac in order to observe the de-excitation of the final nucleus to its ground state.[1]

The rotational transitions connecting states having spins up to about 12 were normally very well defined, and could be identified without question. Some of the transitions between higher spin states were equally well defined, but others were included among several unassigned transitions of comparable energy and intensity. Obviously, these latter assignments are not completely certain, and for the present discussion we have included only transitions whose association with the ground-state rotational band is highly probable. A thorough discussion of assignments will be presented, together with the detailed experimental data, in a more complete publication.

From the transition energies, $E(I\rightarrow I-2)$, we define the rotational constant, A_I, as follows:

$$A_I = \hbar^2/2\mathfrak{J}_I = E(I\rightarrow I-2)/(4I-2), \qquad (1)$$

where $\mathfrak{J}_I$ represents the moment of inertia appropriate to the transition. In Fig. 1 $\log A_I$ has been plotted versus I for the nuclei studied. At low spins, the general features of this plot are well known: (1) a regular decrease in A_I with increasing spin, and (2) smaller slopes (more perfect rotors) associated with lower A_I values. The similarity in rotational properties of all these isotopes at higher spins is very pronounced. The points in all cases (except possibly ^{166}Hf for which there is no information above spin 12) are, or become with increasing spin, quite linear with a common limiting slope of 8 or 9% decrease in A_I per state Furthermore, the absolute A_I values are converging into two groups. Thus, for the $14\rightarrow 12$ transition, five of the seven cases for which there is information have A_{14} values within 2% of 11.05 keV and the other two cases both have A_{14} values of 10.17 keV, within our limits of error (0.3%). It cannot be ruled out that at still higher spins these groups will diverge again; however, our most tentative data at the highest spins rather suggests that they may converge to a single group.

The two nuclei with low A_I values (^{172}W and ^{170}Hf) both have 98 neutrons, and a cursory exam-