culated ratio and the data is within a factor of 2. For Os^{192}, where an asymmetric but "soft" shape is expected, with the wave function smeared over many possible shapes, the calculated ratio is approximately a factor of 10 larger than measured. It is clear that the pairing-plus-quadrupole model calculations, with the strengths of the forces as used, lead to potential wells that are somewhat shallower in the γ coordinate than are needed to fit the experimental data on transition rates. A modification towards the rotational limit would produce a better over-all fit to the data. It will be of interest to make similar comparisons with the Nd, Gd, and Sm nuclei in the lower mass transition region as soon as the numerical calculations become available.

We thank Dr. Krishna Kumar and Dr. Joseph Weneser for informative discussions concerning this work. We would like to express our appreciation to the operating staff of the A. W. Wright Nuclear Structure Laboratory for their assistance in carrying out the measurements.

---

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

[1] O. B. Nielsen, in Proceedings of the Rutherford Jubilee International Conference, Manchester, 1961, edited by J. B. Birks (Heywood and Company, Ltd., London, 1962), p. 137; G. G. Seaman, J. S. Greenberg, D. A. Bromley, and F. K. McGowan, Phys. Rev. 149, 925 (1966); Y. Yoshizawa et al., Nucl. Phys. 46, 78 (1963); E. R. Marshalek, Phys. Rev. 139, B770 (1965).

[2] See, for example, R. G. Stokstad and I. Hall, Bull. Am. Phys. Soc. 12, 35 (1967); J. de Boer, R. G. Stokstad, G. D. Symons, and A. Winther, Phys. Rev. Letters 14, 564 (1965); P. H. Stelson et al., Bull. Am. Phys. Soc. 10, 427 (1965).

[3] A. Bohr and B. R. Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-Fys. Medd. 27, No. 16 (1953).

[4] K. Kumar and M. Baranger, Phys. Rev. Letters 17, 1146 (1966); M. Baranger and K. Kumar, in Perspectives in Modern Physics, edited by R. A. Marshak (Interscience Publishers, Inc., New York, 1966).

[5] K. Kumar, private communication.

[6] These measurements agree substantially with some recent overlapping measurements by W. T. Milner et al., Bull. Am. Phys. Soc. 12, 35 (1967). Also, see F. K. McGowan and P. H. Stelson, Phys. Rev. 122, 1274 (1961); J. de Boer, G. Goldring, and H. Winkler, Phys. Rev. 134, B1032 (1964).

[7] Although the data are consistent with a positive value for the sign of the interference term in all four nuclei, the accuracy of the measurements does not completely exclude the choice of a negative sign. If the negative sign is used, the following $B(E2{:}0^+ \to 2^{+\prime})$ values are obtained for $Os^{186,188,190,192}$, respectively: 0.295 ± 0.060, 0.284 ± 0.042, 0.303 ± 0.045, and 0.206 ± 0.030.

VECTOR POLARIZATION IN d-α SCATTERING

A. Trier* and W. Haeberli
University of Wisconsin, Madison, Wisconsin†

(Received 10 April 1967)

A beam of polarized deuterons has been scattered from a helium target. The results show that d-α scattering is a useful analyzer for deuteron vector polarization for most deuteron energies between 2.5 and 10 MeV. It is also observed that the d-α break-up reaction is strongly dependent on deuteron spin.

Experiments with polarized protons have led to a detailed knowledge of the spin dependence of the proton-nucleus interaction. Very little is known, by comparison, about the interaction of deuterons with nuclei. Polarization experiments are indispensable if one wishes to determine the strength of the deuteron spin-orbit interaction with any degree of accuracy but progress has been hindered by the lack of suitable polarization analyzers. In a number of recent experiments the reaction $He^3(d,p)He^4$ has been used as a polarization analyzer, following a proposal by Galonsky, Willard, and Welton.[1] The deuterons have to be slowed down to an energy of a few hundred keV because the method depends on the assumption that the reaction takes place only with s-wave deuterons. However, the reaction mentioned above only permits the determination of the tensor polarization (alignment parameters) of the deutrons. The reaction is completely insensitive to the vector polarization because the deuteron orbital angular momentum is zero. The vector polarization of the deuterons can in principle be determined from the polarization of the outgoing protons. This has been done in one case.[2] However, the method is usually not practical for intensity reasons, because an additional scattering is necessary to determine the proton polarization.

On the basis of recent analyses of d-α scattering we had reason to believe that this process is sensitive to the vector polarization of the deuterons, not only near the narrow 1.07-MeV resonance, but also over a wide energy range at higher energies.[3-5] In order to measure the vector polarization (or vector analyzing power) in d-α scattering the polarized beam[6] of the Wisconsin tandem accelerator was used. The lack of analyzing reactions for deuteron vector polarization made it necessary to infer the magnitude of the beam polarization from other experiments. Earlier experiments[6] had shown that the mechanism of the polarized ion source is sufficiently well understood to predict the polarization of the proton beam correctly to within 1%. Similarly, the tensor polarization of the deuteron beam, which was measured by use of the reaction $\mathrm{He}^3(d,p)\mathrm{He}^4$, was consistent with the expected value. We therefore postulate that also the vector polarization of the beam is close to the expected value. This assumption seems justified because the atomic interactions in the ion source are well understood and because the corrections for depolarizing effects are small.

The deuteron beam is horizontal and is incident upon a gas cell containing helium. Two CsI scintillation counters and the target cell are located in a horizontal plane at symmetric angles to the left and the right of the incident beam. The polarization axis, which is defined by the magnetic guide field in the ionizer of the polarized ion source, is vertical, i.e., normal to the scattering plane. The differential elastic cross section for a nuclear reaction induced by a polarized beam can be written in the form[7]

$$\sigma(\theta,\varphi)=\sigma_0(\theta)(1+2\langle it_{11}\rangle\langle iT_{11}\rangle\cos\varphi+\langle t_{20}\rangle\langle T_{20}\rangle +2\langle it_{21}\rangle\langle iT_{21}\rangle\sin\varphi+2\langle t_{22}\rangle\langle T_{22}\rangle\cos2\varphi), \quad (1)$$

where $\sigma_0(\theta)$ is the cross section for an unpolarized beam. The spin tensor moments $\langle t_{qk}\rangle$ represent the polarization of the incident beam and the $\langle T_{qk}\rangle$ are the polarization tensor moments describing the scattering process.[8] The beam polarization is, as usual, taken in a right-handed coordinate system with the z axis along the incident beam direction. In the present application it is convenient to take the y axis along the spin direction $\langle\vec{S}\rangle$ of the incident beam. The aximuthal angle φ is measured between the y axis and the normal to the scattering plane $\vec{k}_{\mathrm{in}}\times\vec{k}_{\mathrm{out}}$. The vector polarization $\langle it_{11}\rangle$ is related to $P_y=\langle S_y\rangle$ by $\langle it_{11}\rangle=\frac{1}{2}\sqrt{3}P_y$. Values of the $\langle t_{qk}\rangle$ for our beam are given in Ref. 7. The left-right ratio of counting rates can then be expressed as

$$\frac{\sigma(\theta,\varphi=0)}{\sigma(\theta,\varphi=\pi)}=\frac{1+c+2\langle it_{11}\rangle\langle iT_{11}\rangle}{1+c-2\langle it_{11}\rangle\langle iT_{11}\rangle}. \quad (2)$$

Note that c is the same for scattering to the left and scattering to the right. The second-rank moments which enter in c are known reasonably accurately from previous experiments[5] so that the vector polarization $\langle iT_{11}\rangle$ can be obtained from Eq. 2. For the angles and energies of the present experiment c varied between -0.1 and $+0.2$. In order to eliminate the difference in counter solid angle one reverses the magnetic guide field at the ion source.

The experiment was repeated in a way which made it unnecessary to have prior knowledge of the quantity c. In principle, only a single counter is necessary for this purpose but it is essential to be able to obtain accurately reproducible integration of the incident beam intensity. If measurements are taken with spin up, spin down, and unpolarized beam, and if the runs are normalized to the same number of incident deuterons, the ratios

$$\sigma(\theta,\varphi=0)/\sigma_0(\theta)=1+c+2\langle it_{11}\rangle\langle iT_{11}\rangle,$$
$$\sigma(\theta,\varphi=\pi)/\sigma_0(\theta)=1+c-2\langle it_{11}\rangle\langle iT_{11}\rangle \quad (3)$$

can be measured separately. The two equations obviously yield c and $\langle it_{11}\rangle\langle iT_{11}\rangle$. In the present experiment the beam integration was carried out by placing a thin (400-μg/cm^2) gold foil in the beam in front of the target and monitoring the intensity of deuterons scattered from the foil at an angle of 24° by two solid-state detectors. Both methods gave consistent results.

The measured d-α vector polarizations for center-of-mass scattering angles of 66° and 104° are shown in Fig. 1 and are tabulated in Table I. The uncertainties in polarization (including the uncertainty of the beam polarization) are about ±0.01. The largest values measured are roughly equal to one-half of the max-

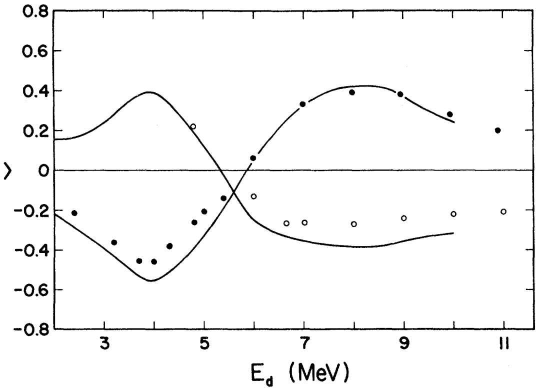

FIG. 1. Vector polarization in d-α scattering for center-of-mass scattering angles 66° (dots) and 104° (circles). The calculated curves are based on the phase shifts of Ref. 5.

Table I. Vector polarization in d-α scattering.

$\theta_{\text{c.m.}}$	E_d	$\langle iT_{11}\rangle^{a}$	$\theta_{\text{c.m.}}$	E_d	$\langle iT_{11}\rangle^{a}$
66°	2.50	−0.21	66°	8.96	0.38
	3.20	−0.37		9.95	0.27
	3.69	−0.46		10.92	0.20
	3.97	−0.46	104°	4.79	0.22
	4.31	−0.39		6.00	−0.13
	4.84	−0.26		6.65	−0.26
	4.96	−0.20		7.00	−0.26
	5.40	−0.14		7.99	−0.27
	5.97	0.06		9.01	−0.25
	6.96	0.33		9.99	−0.22
	7.97	0.39		11.01	−0.21

[a] The uncertainty of $\langle iT_{11}\rangle$ is ±0.01 except for some point where it may reach ±0.02. The main contributions to the error are from counting statistics and uncertainty in beam polarization.

imum possible value ($\langle iT_{11}\rangle_{\max}=\sqrt{3}/2$). Additional measurements for a scattering angle of 86° gave values for $\langle iT_{11}\rangle$ between 0.03 and 0.07 for deuteron energies between 5 and 11 MeV. The solid lines in Fig. 1 represent the predictions from the phase-shift analysis.[5] At all angles measured, the new data confirm the qualitative features of the analysis and, therefore, strengthen the evidence against the proposed $T=0$ levels[4] in Li^6 at 6.8, 7.8, and 9 MeV.

The observation of substantial values of vector polarization in d-α scattering suggests the possibility of producing vector-polarized deuteron beams by bombarding deuterium targets with beams of high-energy α particles, similar to the method used by Rosen[9] and others to produce polarized protons. Bombardment of a deuterium target, e.g., with 18-MeV α particles would yield recoil deuterons at $\theta_{\text{lab}}=30°$ with an energy of 12 MeV and a vector polarization of about $\langle it_{11}\rangle=-0.3$. The polarization is estimated on the basis of an extrapolation of the measurements to $\theta_{\text{c.m.}}=120°$.

In the course of the present experiment we also observed the left-right intensity ratio of protons from deuteron breakup on He^4. For deuteron energies above 9 MeV and $\theta_{\text{lab}}=45°$ and 60°, the polarization effects in deuteron breakup are large, in fact, about as large as in d-α scattering at 45° and 9 MeV, but opposite in sign. The large asymmetry is confined to the part of the proton spectrum which is dominated by the n-α final-state interaction.[10] In cases like the present one, where the final-state interaction is strongly spin dependent, the use of a polarized deuteron beam offers an interesting new method of separating the break-up continuum from the final-state interaction peak.

We should like to thank Dr. P. Extermann and Mr. L. Veeser for their help in the experiment.

---

*Now at the Department of Physics, University of Chile, Santiago, Chile.

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

[1] A. Galonsky, H. B. Willard, and T. A. Welton, Phys. Rev. Letters 2, 349 (1959).

[2] F. Seiler, E. Baumgartner, W. Haeberli, P. Huber, and H. R. Striebel, Helv. Phys. Acta 35, 385 (1962).

[3] R. J. N. Phillips, Phys. Rev. Letters 3, 101 (1959).

[4] L. S. Senhouse, Jr., and T. A. Tombrello, Nucl. Phys. 57, 624 (1964).

[5] L. C. McIntyre and W. Haeberli, Nucl. Phys. A91, 382 (1967).

[6] W. Gruebler, P. Schwandt, T. J. Yule, and W. Haeberli, Nucl. Instr. Methods 41, 245 (1966).

[7] P. Extermann, Nucl. Phys. 95A, 615 (1967). In contrast to double scattering, where $\langle t_{21}\rangle$ results in a $\cos\varphi$ dependence, a $\sin\varphi$ dependence occurs here because $\langle t_{21}\rangle$ from a polarized ion source is purely imaginary.

[8] As always, the $\langle T_{qk}\rangle$ can be interpreted as the polarization of the outgoing beam in the inverse reaction, induced with an unpolarized incident beam. The definition of the spherical tensor moments used here is that of W. Lakin, Phys. Rev. 98, 139 (1955).

[9] L. Rosen and J. E. Brolley, Phys. Rev. 107, 1454 (1955). This method is now being used by E. M. Bernstein, G. G. Ohlsen, V. S. Starkovich, and W. G. Simon, Bull. Am. Phys. Soc. 12, 482 (1967).

[10] G. G. Ohlsen and P. G. Young, Phys. Rev. 136, B1632 (1964).