TABLE I. Experimental and theoretical values of the ratio $\sigma(0°)/\sigma(90°)$.

Final spin	$\left[\frac{\sigma(0°)}{\sigma(90°)}\right]_{obs}$	$\left[\frac{\sigma(0°)}{\sigma(90°)}\right]_{s.p.e.}$	$\left[\frac{\sigma(0°)}{\sigma(90°)}\right]_{m.p.e.}$
1/2	1.6	1.57	1.31
3/2	1.2	1.25	1.15
7/2	0.7	0.79	0.84

the W.K.B. approximation, and l values ≥ 3 for the deuterons and ≥ 6 for the protons were neglected. It is estimated that 90 percent of each reaction is due to l values within these limits.

In the case of the reaction $Ni^{58}(d,p)Ni^{59}$ (Fig. 1), the shell model predicts a state $3/2^-$ for the final nucleus. The results are seen to be in good agreement with this prediction, although they are not inconsistent with a final state of spin $5/2^-$. In the case of the reaction $Ni^{60}(d,p)Ni^{60*}$ (Fig. 2), the shell model does not predict the spin, although since the lowest available levels are $P^{3/2}$, $f^{5/2}$, and $P^{1/2}$, an odd parity is strongly implied. The observed results are in reasonable agreement with a final state $7/2^-$, and are totally inconsistent with any of the other assumptions (an estimate of the theoretical curve for a $9/2^-$ final state indicates an approximately isotropic angular distribution). The third proton group (Fig. 3) corresponds to a transition to a level at 1.7 Mev in Ni^{59}, or at 1.3 Mev in Ni^{61}. The results are seen to be in excellent agreement with the theoretical results for a $1/2^-$ final state.

The theoretical curves in Figs. 1 to 3 have been calculated for single-particle excitation in the compound nucleus [$F(J)=1$ except for $F(0)=\frac{1}{2}$, in Wolfenstein's[2] Eq. (9)]. If the alternative assumption of multiple particle excitation [$F(J)=2J+1$] is employed, the resulting angular distributions are somewhat more isotropic. Table I gives the ratio of the differential cross section at 0° to that at 90° as observed and as calculated from the alternative assumptions of single-particle excitation (s.p.e.) and multiple-particle excitation (m.p.e.). The assumption of single-particle excitation is seen to agree somewhat better with the observed results, but the difference is not completely definitive.

The results presented here appear to corroborate the statistical theory of Wolfenstein. We should like to point out that for reactions in which the theory is applicable and in which individual proton groups may be resolved, an analysis of angular distribution data in terms of the statistical theory may be expected to give significant information concerning the spins of the states involved.

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[1] Additional work using separated isotopes is planned to settle this point among others.
[2] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[3] L. Wolfenstein, Phys. Rev. **82**, 690 (1951).
[4] P. F. A. Klinkenberg, Revs. Modern Phys. **24**, 63 (1952).

Polarization of High-Energy Protons Scattered by Complex Nuclei*

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WHEN a nucleon of several hundred Mev collides with a nucleus, there is no *a priori* reason to believe that the force it feels is the force exerted on low-energy particles as described, for example, by the shell model. However, it is interesting to attempt to describe the process in terms of elementary interactions with the individual nucleons. With the impulse approximation[1] one can indeed formulate such a scattering problem, provided the nucleon wave function is known. The lack of knowledge of detailed nuclear wave functions is what limits the applicability of such calculations to processes involving deuterons.

TABLE I. Percentage polarization for scattering of protons at various angles. θ is the scattering angle in the center of mass of the nucleon-nucleon system. Except for small relativistic effects this is twice the laboratory angle.

θ	Percent polarization p-d	p-α
30°	18%	43%
45°	35	79
60°	40	92

If one observes, however, that the entire dependence of the matrix element upon the nucleon wave function is contained in the "sticking factor" (overlap integral between the initial and final states), and that the polarization is essentially the ratio of two cross sections, then one is led to suspect that for nuclei possessing a sufficient degree of symmetry, the sticking factors cancel out and the polarization may be calculated without any knowledge of the nuclear wave function. It can be shown that the deuteron and all alpha-particle nuclei have this property. Furthermore on this model all alpha-particle nuclei should give the same polarization.

A method of constructing an S matrix for the scattering from a complex nuclei in terms of the n-p and p-p phase shifts has already been described.[2] Using the tensor force p-p phase shifts of Goldfarb and Feldman,[3] and the n-p phase shifts of Swanson,[4] polarizations have been calculated for incident protons of 240 Mev. The polarizations at various angles are given in Table I.

Note that the phase shifts used give qualitative agreement with the polarization effects found in nucleon-nucleon scattering. It is significant, then, that interference and spin-correlation effects work in such a way as to markedly increase the polarization, in agreement with recent experiments.[5]

It is tempting to generalize the above results, arguing that most light nuclei consist of an alpha-particle-like core plus a few excess nucleons, so that most of the scattering is from the alpha-particle core. On the basis of this picture one may argue that all nuclei of $4 \leq Z \leq 20$ should give about the same polarizations.

A more detailed paper will appear shortly.

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[1] G. F. Chew, Phys. Rev. **74**, 809 (1948).
[2] S. Tamor, Phys. Rev. **93**, 227 (1954).
[3] L. J. B. Goldfarb and D. Feldman, Phys. Rev. **88**, 1099 (1952).
[4] D. R. Swanson, Phys. Rev. **89**, 749 (1953).
[5] Oxley, Cartwright, Rouvina, Baskir, Klein, Ring, and Skillman, Phys. Rev. **91**, 419 (1953); Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954).

Polarization of Fast Protons Scattered by Nuclei*

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THE polarization of high-energy protons scattered by nuclei has recently been reported.[1] According to the work of Marshall, Marshall, and de Carvalho,[1] the greater part of the polarized component of the scattered beam appears to be elastically scattered by the nucleus. The elastic scattering of fast particles by nuclei is often described using the "optical model";[2] however, it is clear that the simple optical model must be modified by spin-interactions if it is to lead to polarization. For instance, Fermi[3] has recently proposed adding to the optical model potential a spin-orbit interaction which is 15 times the "Thomas correction." This choice was motivated by the strength of the spin-orbit splitting supposed in the Mayer-Jensen shell model of nuclear structure.

In the present note, we wish to remark that a term similar to that suggested by Fermi can arise naturally in the Serber model of high-energy nuclear reactions. In the Serber model, one pictures a fast neutron or proton in a nucleus as scattering against individual nucleons as if they were essentially free. This permits one to describe the scattering by the nucleus in terms of the scattering by free nucleons. In contrast to this are the theories which suppose collective properties of the bound nucleons to determine the characteristics of the interaction with an incoming particle.

To find the implications of the Serber model, let us first consider the scattering amplitude for proton-proton scattering, $(\mathbf{q}'|t|\mathbf{q})$, where $\mathbf{q}$ and $\mathbf{q}'$ are the respective initial and final relative moments. It will prove convenient to use the parametric representation of Wolfenstein and Ashkin[4] for $(\mathbf{q}'|t|\mathbf{q})$. This will permit us to express the polarization for nucleon-nucleon and nucleon-nucleus collisions in terms of the same set of parameters. Since the polarization appears to be large at small scattering angles[1] θ, we shall simplify the discussion by expanding t in powers of θ, keeping no more than the linear term. (The general expressions may be easily written down, but are too lengthy to give here.) Then

$$(\mathbf{q}'|t|\mathbf{q})=A_0+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2A_0'+(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot(\mathbf{q}'\times\mathbf{q}/q'q)A_1+\cdots, \quad (1)$$

where the A's are complex constants. The $\boldsymbol{\sigma}$'s are the proton spin operators. For n-p scattering a similar expression will obtain, the constants A being replaced by a new set of constants B, characteristic of the n-p interaction.

The optical model potential[5] is expressed in terms of t by

$$v_e=\frac{A}{V_A}\langle t\rangle\int_{V_A}\exp[-i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{x}]d^3x, \quad (2)$$

where A is the mass number and V_A the volume of the nucleus. The integral is taken over the nuclear volume. Also $\mathbf{p}$ and $\mathbf{p}'$ are the initial and final momenta, respectively, of the scattered proton. By $\langle t\rangle$, we mean the average of t for the neutrons and protons in the nucleus, these being considered as "target particles." This average includes an average over their spins. To the extent that these spins are randomly oriented, terms linear in their spin operators tend to average to zero. If, for the sake of argument, we consider $\boldsymbol{\sigma}_2$ in Eq. (1) to refer to a nucleon in the nucleus, then we approximate $\langle t\rangle$ by setting equal to zero in Eq. (1) the terms linear in $\boldsymbol{\sigma}_2$. This gives

$$v_c=\frac{A}{V_A}\left[\bar{A}_0+\boldsymbol{\sigma}\cdot\left(\frac{\mathbf{q}'}{q'}\times\frac{\mathbf{q}}{q}\right)\bar{A}_1\right]\int_{V_A}\exp[-i(\mathbf{p}'-\mathbf{p})\cdot\mathbf{x}]d^3x, \quad (3)$$

where $\boldsymbol{\sigma}$ now is the spin operator of the bombarding proton. Here $\bar{A}_0$ and $\bar{A}_1$ represent the average of the amplitude of Eq. (1) for p-p and n-p collisions; i.e., $\bar{A}_0=A^{-1}[ZA_0+(A-Z)B_0]$, etc., where Z is the atomic number of the nucleus.

The polarization for p-p scattering is

$$P_{p\text{-}p}=\langle t^+\sigma_1 t\rangle_{\text{spin}}/\langle t^+t\rangle_{\text{spin}} \quad (4)$$

$$\simeq 4\,\text{Re}[(A_0+A_0')A_1^*]\sin\theta_{\text{lab}}/(|A_0|^2+3|A_0'|^2), \quad (5)$$

to first order in the laboratory scattering angle, θ_{lab}. By σ_1 we mean the component of $\boldsymbol{\sigma}_1$ in the direction $\mathbf{q}'\times\mathbf{q}$. The n-p polarization is obtained by replacing the A's by B's in Eq. (5).

We shall calculate the polarization for the scattering of a proton by the nucleus in the Born approximation, as did Fermi,[3] which does not seem unreasonable for the lighter nuclei. This is obtained by replacing t by v_c in Eq. (4):

$$P_{p\text{-nuc}}\simeq 4\,\text{Re}[\bar{A}_0^*\bar{A}_1]\sin\theta_{\text{lab}}/|\bar{A}_0|^2. \quad (6)$$

The difference between Eqs. (5) and (6) has a simple origin. For the nucleon-nucleon scattering the *current densities* are averaged over spins. For scattering by a nucleus the *scattering amplitude* is averaged over the spins of the target nucleons.

There seem to be no very simple relations between Eqs. (5) and (6). Indeed, there are 12 real parameters at our disposal. To determine these, we have:

(1) $\text{Im}(A_0)=-v\sigma_{p\text{-}p}/2(2\pi)^3$, where v is the relative velocity of the colliding protons and $\sigma_{p\text{-}p}$ is their total cross section[5] [there is a similar expression for $\text{Im}(B_0)$];
(2) the scattering cross sections in the forward direction;
(3) the $\text{Re}[v_c]$;[6,7]
(4) $P_{p\text{-}p}$, $P_{p\text{-}n}$, and $P_{p\text{-nuc}}$.

We have verified by direct computation that it is possible to fit these eight data (to the extent that they are known) by a considerable range of choices of the twelve available parameters.

On the other hand, more elaborate observations of nucleon-nucleon polarization may eventually provide sufficient information concerning the scattering amplitudes to permit a test of Eq. (6). This equation may also be used as a test of specific models of nucleon-nucleon scattering if the Serber model is accepted.

We finally conclude that the observed[1] polarization does not at present seem in disagreement with the Serber model.

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1 Oxley, Cartwright, Rouvina, Baskir, Klein, Ring, and Skillman, Phys. Rev. **91**, 419 (1953); Marshall, Marshall, and de Carvalho, Phys. Rev. **93**, 1431 (1954); Chamberlain, Segrè, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954).
2 Fernbach, Serber, and Taylor, Phys. Rev. **75**, 1352 (1949).
3 E. Fermi, Nuovo cimento **11**, 407 (1954).
4 L. Wolfenstein and J. Ashkin, Phys. Rev. **85**, 947 (1952).
5 K. M. Watson, Phys. Rev. **89**, 575 (1953) and N. C. Francis and K. M. Watson, Phys. Rev. **92**, 291 (1953). The application of the optical model in this case is quite straightforward, it being necessary of course to use properly antisymmetrized (in charge and ordinary space) wave functions in evaluating the nucleon-nucleon scattering amplitudes t. In this connection we might clarify a statement made in the second reference above in the paragraph following Eq. (20). It was stated that the discussion of the optical model applied for nucleons when "exchange scattering" is negligible. This did not mean exchange effects for the two-nucleon scattering amplitudes, but rather some additional exchange corrections (which are expected to be small at high energies) due to the nuclear binding. We plan to publish a quantitative analysis of this point in the near future.
6 T. B. Taylor, Phys. Rev. **92**, 831 (1953).
7 R. Jastrow, Phys. Rev. **82**, 261 (1951).

Neutron Absorption Cross Section of U^{235} at 2200 m/sec*

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The total cross section of U^{235} for neutrons in the thermal energy region has been measured by means of a transmission experiment. The neutron velocity was determined by a time-of-flight method utilizing the Brookhaven slow chopper. The absorption cross section at a neutron velocity of 2200 m/sec was found to be 691±5 barns.

The slow chopper is an instrument that allows a burst of pile neutrons to pass periodically to a detector several meters distant.[1] The velocity of the neutron is determined by measuring the time of flight of the neutron to the detector (an enriched BF_3 counter). The flight time is measured electronically, the standard being a one-megacycle quartz crystal. The major uncertainty in the time-of-flight measurement is the determination of the zero time, i.e., the time the neutrons pass through the shutter. This time is determined by a calibration procedure using the c-axis lattice spacing in graphite (6.70A) measured by x-ray spectrometer techniques. The calibration is accurate to 0.25 percent of the wavelength setting.[2] The transmission of the U^{235} sample for the timed neutrons is obtained by measuring the detector counting rate with the sample in and out of the beam. Background counting rates on these two measurements are obtained by inserting a 0.010-in. Cd foil in the beam. The U^{235} sample in the beam is placed in good geometry with respect to the detector; consequently the transmission is related to the total cross section by the expression

$$T(\lambda)=\exp[-x\ \Sigma_i N_i\sigma_i(\lambda)],$$

where $T(\lambda)$= transmission of sample at neutron wavelength λ, x= sample thickness, N_i= No. atoms/unit volume of isotope i, and $\sigma_i(\lambda)$= total neutron cross section at wavelength λ of isotope i.

Measurements were made on five samples of uranium metal, principally U^{235} and U^{238} having various isotopic abundances and thicknesses. In the thermal region the samples of high enrichment of U^{235} are best suited for an accurate determination of the absorp-