# POLARIZATION IN HIGH-ENERGY INELASTIC SCATTERING

R. M. Haybron,* H. McManus, and A. Werner
Michigan State University, East Lansing, Michigan

and

R. M. Drisko
University of Pittsburgh, Pittsburgh, Pennsylvania

and

G. R. Satchler
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received 27 January 1964)

The impulse approximation applied to high-energy nucleon-nucleus scattering (~100 MeV or higher) expresses the inelastic transition probability in terms of the free two-nucleon scattering amplitude.[1] There is considerable evidence that approximating the projectile motion by plane waves gives a very satisfactory explanation of the polarization produced in terms of the properties of the nucleon-nucleon interaction (see reference 1). However, it is also known that distortion effects (due to elastic scattering of the nucleon before and after the inelastic event) are still large at these energies, and they alone can produce substantial polarizations if a spin-orbit coupling term is included in the distorting potential. It is our purpose here to present some preliminary results of calculations including polarization produced by both mechanisms in the excitation of the $2^+$ level of $^{12}C$ at 4.43 MeV to determine the importance of the spin-dependent distortion effects.

The transition amplitude in the distorted-wave impulse approximation has the form

$$A = \sum_{m_a' m_b'} \langle \psi_f(\vec{r}')\chi_{m_b m_b'}^{(-)}(\vec{r},\vec{k}_b)|M(\vec{q})\delta(\vec{r}-\vec{r}')|\chi_{m_a' m_a}^{(+)}(\vec{r},\vec{k}_a)\psi_0(\vec{r}')\rangle, \tag{1}$$

where $\vec{k}_a, m_a$ and $\vec{k}_b, m_b$ are the initial and final momentum and spin states of the bombarding nucleon and $\vec{q}=\vec{k}_f-\vec{k}_0$ is the momentum transferred in the collision. The functions $\chi^{(+)}$ and $\chi^{(-)}$ are distorted waves produced by the elastic-scattering optical potential which include the effects of reflection, refraction, and absorption. Since the optical potential contains a spin-orbit interaction, the spin projection of the incident nucleon may be flipped from $m_a$ to $m_a'$ before the inelastic scattering and from $m_b'$ to $m_b$ afterwards. The intermediate spin states must be summed over since they are not observed. The quantity $M(\vec{q})$ is the two-nucleon scattering amplitude which depends on the initial projectile energy and the momentum transfer $\vec{q}$ and acts on the spins of the incident and struck nucleons. The isospin dependence of $M(\vec{q})$ has been omitted for convenience.

It is not strictly correct to evaluate $M(\vec{q})$ at the momentum transfer $\vec{q}=\vec{k}_b-\vec{k}_a$ since refraction introduces other momenta. Instead we should average $M(\vec{q}')$ over the momentum-transfer distribution introduced by the distorted waves. However, since the elastic scattering at these energies is mostly in the forward direction, it is reasonable to approximate this average by $M(\vec{q})$. (More complete calculations in which this approximation is not made will be reported later.) Using this approximation, the amplitudes (1) have been evaluated exactly by modifying an existing distorted-wave computer code.[2]

When the nuclear spin-flip matrix element vanishes ($\lambda=0$ in the notation of reference 1) and the spin-orbit coupling in the optical potential is ignored, the polarization obtained from (1) is given by

$$P_{\rm NS} = 2\,{\rm Re}AC^*/(|A|^2+|C|^2), \tag{2}$$

where $A$ and $C$ are the central and spin-orbit parts of the two-nucleon potential, respectively. This is the same result obtained in the Born approximation where $\chi^{(+)}$ and $\chi^{(-)}$ are replaced by plane waves. It should be remarked that if nuclear spin flip occurs ($\lambda \neq 0$), the polarization obtained by omitting the optical spin-orbit coupling is not equal to the plane-wave result (except for $\lambda=\infty$). The polarization has been calculated at energies of

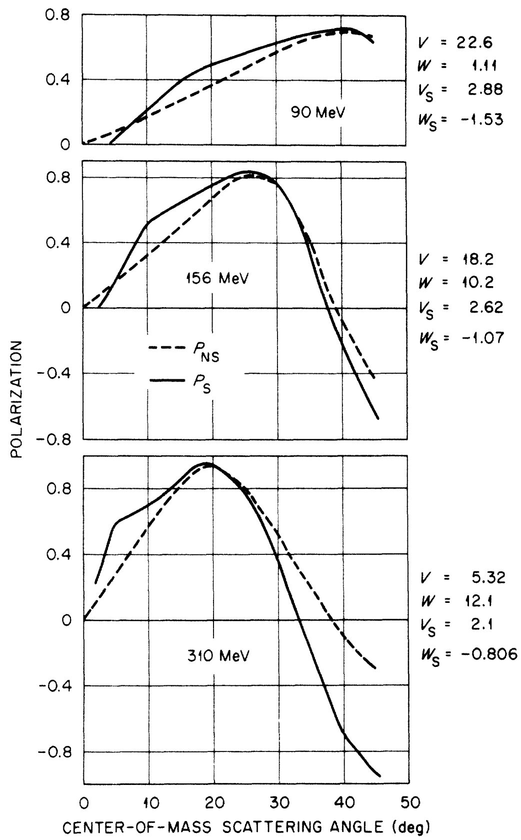


FIG. 1. Polarizations are shown which were produced with no spin-orbit coupling in the distorting potential ($P_{NS}$) and with spin-orbit coupling included ($P_S$). $P_{NS}$ is identical to the plane-wave result for this case ($\lambda = 0$). The optical potential used was of the Saxon-Wood type with a real, central strength $V$ of radius $r_0 = 1.0$ F and diffuseness $a = 0.5$ F, an imaginary strength $W$ of radius $r_0' = 1.34$ F and diffuseness $a = 0.5$ F. The spin-orbit coupling was of the derivative type with real strength $V_S$, imaginary strength $W_S$, radius 1.0 F, and diffuseness 0.5 F. Values of $V$, $W$, $V_S$, and $W_S$ are given in MeV.

90, 156, and 310 MeV using (2) and also from (1) with the spin-orbit distortion included. These are shown in Fig. 1 labeled, respectively, NS (no spin-orbit) and S (spin-orbit). The data now available are not accurate enough to distinguish between these curves, although there is perhaps some preference for the spin-orbit case.

The spin-orbit effect can be discussed conveniently in the following approximate manner. The amplitude (1) can be written, keeping first-order terms in the spin-orbit distortion, as

$$A = F\langle m_b | M' | m_a \rangle \tag{3}$$

for a nuclear transition in which there is no spin flip. $F$ contains all structure effects and $M'$ is

$$M' = A + C\vec{\sigma}\cdot\hat{n} + (f\vec{\sigma}\cdot\hat{n})(A + C\vec{\sigma}\cdot\hat{n}) + (A + C\vec{\sigma}\cdot\hat{n})(g\vec{\sigma}\cdot\hat{n}). \tag{4}$$

The unit vector $\hat{n}$ is the normal to the scattering plane. The quantities $f$ and $g$ (which depend on $\vec{q}$) are related to the polarization produced in the final and initial channels, respectively, as can be illustrated in the following way. Calculation of the polarization implied by (4) yields

$$P_A = \frac{2\{\mathrm{Re}AC^* + (|A|^2 + |C|^2)\,\mathrm{Re}(f+g)\}}{|A|^2 + |C|^2 + 4\,\mathrm{Re}(AC^*)\,\mathrm{Re}(f+g)}, \tag{5}$$

where we have kept terms to first order in $f$ and $g$ as before. In the case of a spin-independent nucleon-nucleon interaction with $C = 0$, (5) reduces to

$$P_0 = 2\,\mathrm{Re}\{f + g\}, \tag{6}$$

so that $P_0$ is the polarization which would be produced by distortion alone. Using (2) and (6), the net polarization due to both nucleon-nucleon effects and optical distortions given by (5) becomes

$$P_A = (P_{NS} + P_0)/(1 + P_{NS}P_0). \tag{7}$$

This approximate result for $P_A$ is shown in Fig. 2 at 90, 156, and 310 MeV compared to the exact result (labeled $P_S$) obtained from the amplitude (1). Also shown is $P_0$ at the three energies.

This comparison is essentially a test to determine whether the spin-orbit portion of the distorting optical potential can be treated as a perturbation. The deviations of $P$ from $P_S$ are seen to increase with increasing optical polarization which is undoubtedly due to neglect of higher order terms in (4) and (5). These results indicate that our point of view is essentially correct, that the polarization produced before and after the inelastic event by the spin-orbit part of the optical potential simply adds to that produced by the nucleon-nucleon scattering. These results would not obtain if the spin-orbit potential substantially affected the spatial part of the scattering wave or if the distortion polarization were large compared to that produced by the two-nucleon interaction, in other words if it were not a perturbation in both $\vec{r}$ space and spin space.

The fact that inclusion of the spin-orbit coupling in the elastic optical potential materially alters the inelastic polarization from the Born approximation result apparently contradicts earlier conclusions by Kohler[3] and essentially agrees with work reported by Hooten and Ashcroft.[4] The po-

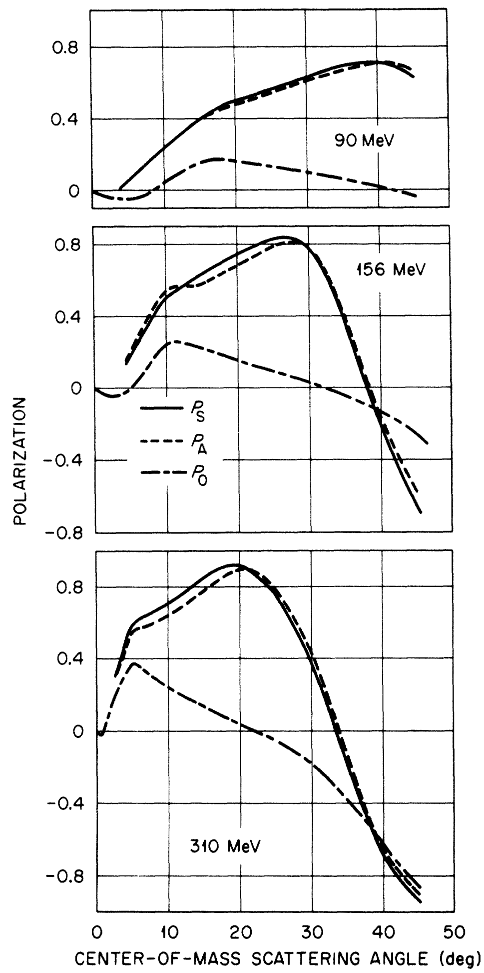


FIG. 2. The polarization $P_0$ is that produced by distortion effects alone. The exact polarization $P_S$ is compared to $P_A$ which was calculated treating spin-dependent distortions as a perturbation.

larization curves displayed in the latter reference bear a considerable resemblance to the predictions of Eq. (7) (shown in Fig. 2).

Calculations using the detailed hole-particle wave functions of Gillet[5] for $^{12}C$, $^{16}O$, and $^{40}Ca$ are currently being performed and will be presently reported. These are expected to give very

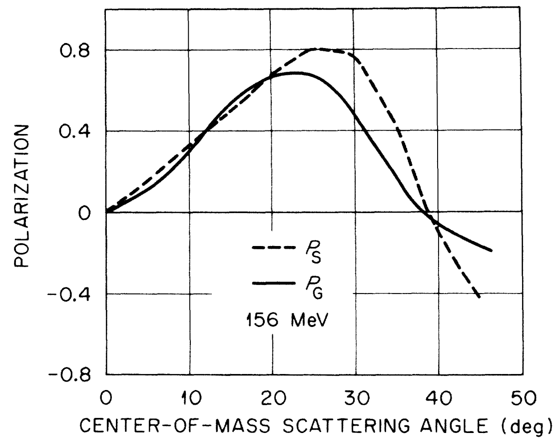


FIG. 3. The polarization obtained without spin-dependent distortions using $L$-$S$ coupled nuclear wave functions ($P_S$) is compared to that obtained using Gillet's wave functions (labeled $P_G$).

good values of the maximum differential cross section (which is too small by a factor of two for simple $L$-$S$ coupled states), since they are designed to reproduce the collective enhancements known to characterize transitions in these nuclei. A Born approximation calculation of the $2^+$ level of $^{12}C$ excited at 156 MeV using Gillet's wave functions shows an enhancement in the cross section of about 40%. The polarization so obtained is shown in Fig. 3 compared to $P_{NS}$ from Fig. 1. The partial agreement is encouraging but not conclusive until more complete calculations including distortion effects are completed.

---

*Presently on leave at Oak Ridge National Laboratory, Oak Ridge, Tennessee.

[1]A. K. Kerman, H. McManus, and R. M. Thaler, Ann. Phys. (N.Y.) 8, 551 (1959).

[2]R. H. Bassel, R. M. Drisko, and G. R. Stachler, Oak Ridge National Laboratory Report No. 3240, 1962 (unpublished); G. R. Satchler (to be published).

[3]H. S. Kohler, Nucl. Phys. 9, 49 (1958).

[4]D. J. Hooten and N. W. Ashcroft, Proc. Phys. Soc. (London) 81, 193 (1963).

[5]V. Gillet, thesis, Paris, 1962 (unpublished).