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Polarizations in Heavy-Ion Reactions

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The polarizations of products of quasielastic heavy-ion reactions are discussed in the framework of the distorted-wave Born approximation and are shown to depend upon the bombarding energy, Q value, and specific reaction products. A sign change of these polarizations (which is unrelated to negative-angle scattering) is expected as a function of energy loss. Polarizations of the reaction products may be of opposite sign.

In two recent experiments[1,2] polarizations of reaction products from heavy-ion–induced transfer reactions were measured and were shown to depend upon the Q value of the reaction. The purpose of this Letter is to demonstrate that the signs of polarizations in quasielastic heavy-ion reactions depend strongly upon the reaction products, the bombarding energy, and the Q value and that the individual reaction products may have opposite polarizations. Wilczynski,[3] using a simple frictional model to obtain polarizations, suggested that observation of opposite polarizations for products of deep-inelastic and quasielastic reactions would give evidence of predominant negative-angle scattering (scattering across the beam axis) for the deep-inelastic process. It is shown below that for the quasielastic reactions alone a sign change of the polarizations, which is *unrelated* to negative-angle scattering, is expected as a function of energy loss. The discussion is primarily concerned with the reasonably well understood single-step quasielastic process since the mechanism of the deep-inelastic process is still in doubt.

The direction of polarization deduced from a commonly used frictional model is depicted in Fig. 1. As the two nuclei come in contact, the frictional force starts the two bodies rotating. In a repulsive potential, the sign of the polarization has the sense shown in Fig. 1(a). If on the other hand the projectile is scattered to negative angles [Fig. 1(b)], the opposite polarization will be obtained. In each case the ejectile and residual nucleus have the same polarization. In addition to its appealing simplicity, this simple frictional model gives correctly the direction of polarization for Coulomb excitation, a process for which the Q value is negative, and the polarization, while it varies in magnitude, is always of one sign.[4] However, for unphysical cases of Coulomb excitation, i.e., zero or negative excitation energy, the calculated polarization vanishes or is of opposite sign to the physical case.[4] As will be

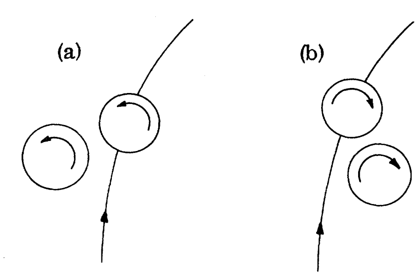

FIG. 1. Description of polarization resulting from a simple frictional model for (a) a repulsive potential and (b) attractive potential.

demonstrated below, the conditions which produce these opposite polarizations for Coulomb excitation can occur at negative Q values when there is mass or charge transfer, and hence the simple arguments about frictional forces producing a given sign of polarization do not hold. The arguments to determine quasielastic polarizations remain straightforward but rely upon a knowledge of the reaction products.

Some of the results presented below are similar to those which could be obtained from Brink's conditions[5] for maximizing cross sections, but the treatment here is more general. To a certain degree the following arguments are similar to those made by Newns[6] to obtain the limiting value of the proton polarization in unpolarized (d,p) reactions; however, the semiclassical nature of heavy-ion reactions allows the arguments to be extended further, and there are complicating features in the heavy-ion case which are not found in (d,p). Spin-orbit interactions, which can have a large effect upon polarizations, are assumed to be negligible for heavy ions. The same assumption, made by Newns, was shown to be a poor one for (d,p) reactions.

Since the distorted-wave Born approximation (DWBA) has generally been so successful for quasielastic reactions, I follow that formalism and write the transition amplitude T, using the notation of Satchler,[7] in the *absence* of spin-orbit interactions,

$$T_{m_bM_B,m_aM_A}\sim\sum_{L,s,j}\langle J_AM_Ajm_j|J_BM_B\rangle\langle s_bm_bsm_s|s_am_a\rangle\langle LMsm_s|jm_j\rangle\beta_L^M, \tag{1}$$

where $J_{A,B}$, $M_{A,B}$ refer to the target–residual-nucleus system and $s_{a,b}$, $M_{a,b}$ to the projectile-ejectile system. L is the angular momentum transferred from (or to) the orbit and M is the projection of L along the z axis. The dynamics of the reaction are contained in β_L^M. For simplicity we shall assume single values for L, s, and j.

Detailed calculations of β_L^M and the polarizations follow closely from Kahana[8] and will be presented elsewhere; only an outline of the calculations and the results is given here. The z axis is chosen as the normal to the reaction plane in this discussion since it is convenient to calculate polarizations along that axis. In this coordinate system[7]

$$\beta_L^M\sim\sum_{\substack{l_i,l_f\\m_i,m_f}}\langle l_fm_fLM|l_im_i\rangle i^{l_i-l_f}Y_{l_i}^{m_i*}(\tfrac{1}{2}\pi,0)Y_{l_f}^{m_f}(\tfrac{1}{2}\pi,\theta_f)I_{l_il_fL}, \tag{2}$$

where l_i and l_f are the incoming and outgoing partial waves and $I_{l_il_fL}$ are the radial integrals.

In the heavy-ion transfer process the strong absorption on one hand and the form factor on the other allow only a narrow window of partial waves, centered at the grazing angular momentum, l^0, to contribute to the reaction. The particular partial waves in the entrance and exit channels which contribute most strongly are close to those where the magnitudes of the S matrices for elastic scattering are 0.5 in each channel.

As in Ref. 8 we can parametrize the radial integrals $I_{l_il_fL}$ in Eq. (2) by Gaussians in l_i and l_f peaked at l_i^0 and l_f^0. When l_i and l_f are large, the M dependence of the Clebsch-Gordan coefficient $\langle l_fm_fLM|l_im_i\rangle$ can be approximated by an element of the rotation matrix $d_{M,l_i-l_f}{}^L(\beta)$ where β is given by $\cos\beta=m_i/[l_i(l_i+1)]^{1/2}$. Throughout we consider reactions dominated by the Coulomb field (no negative-angle scattering) and choose $\vec{Z}=\vec{k}_f\times\vec{k}_i$ so that the partial waves which contribute to the reaction have $m_i\approx l_i$, hence $\beta\approx0°$. The Clebsch-Gordan coefficient then will be largest for $M=l_i-l_f$.[9]

If $l_i^0=l_f^0$, a case which gives the best spectroscopic information because of the resulting L dependence of the cross section,[8] the $M=0$ term of Eq. (2) is largest, the $M>0$ and $M<0$ terms are equal, and the polarization is zero. If l_f^0 and l_i^0 differ by more than L, the radial integrals are largest for the maximum difference in l_i-l_f, and the Clebsch-Gordan coefficient gives strong preference for $M=+L$ or $M=-L$ depending upon whether $l_f^0<l_i^0$ or $l_f^0>l_i^0$. Thus, in general, strong polarization would be expected when $l_f^0\gg l_i^0$, and strong polarization of the *opposite sign* occurs when $l_f^0\ll l_i^0$.

The Q value at which the direction of the transferred angular momentum is expected to change sign is determined by the condition $l_i^0=l_f^0$, a condition which depends upon the bombarding energy and the charges of the particles as well as their masses. In general, different reaction products will show a change of sign of polarization at different Q values although for no charge change or mass change, of course, the condition $l_i^0 = l_f^0$ is satisfied when $Q=0$ for all bombarding energies. For charge stripping, $l_i^0 = l_f^0$ occurs at some negative Q value so that as a function of increasing energy loss there is an expected change in sign in the direction of the transferred angular momentum, which is *unrelated* to negative-angle scattering.

With the assumptions made above, kinematics determine the direction of the transferred angular momentum uniquely, but *not* the polarization of the final nuclei. These polarizations must be determined from Eq. (1). Some specific examples are shown in Table I where for a fixed Q value, chosen so $M=+L$, calculations of polarizations for the (^{16}O, ^{15}O) reaction to different final states J_B in a fictional nucleus are presented. $J_A=0$ has been chosen so that the weighting factor for β_L^M in Eq. (1) reduces to $\langle LMs_b\, -m_b | J_B M_B\rangle$. The scattering angle at which the polarization is calculated is not crucial here since for bell-shaped angular distributions nearly constant values of polarization are obtained. It can be seen that for these cases the polarization of the target is of constant sign, but the projectile polarization changes from case to case, a result contrary to the simple frictional-model expectation. If the spins of ejectile and residual nucleus were reversed, the two columns of polarizations in Table I would be interchanged. It is thus possible to measure opposite polarizations if only the ejectile or only the residual nucleus were measured, or even possible, as is discussed below, to obtain zero net polarization if the sum of the two polarizations were measured. The possibility of ejectile excitation in heavy-ion reactions complicates the simple picture found in (d,p) reactions considerably and makes predictions of residual polarization considerably more difficult.

Since the deep-inelastic reaction mechanism is not completely understood, it is interesting to apply tentatively the quasielastic results to the recent polarization experiments.[1,2] Extension of the arguments for the quasielastic cases to the deep-inelastic processes would lead to the conclusion that $l_f < l_i$ because of the large negative Q values in the deep-inelastic reactions. This would imply strong polarization for the transferred angular momentum and hence for the *sum* of the projections of the intrinsic angular momenta of the fragments. The strong polarization of the transferred angular momentum does not, however, determine the individual fragment polarizations. In experiments where only one fragment polarization is measured,[1] either sign may be obtained depending upon states populated in the other unobserved fragment. This case is similar to that shown in Table I except that many final states are averaged over in the residual nucleus.

For the γ-ray circular-polarization measurement,[2] the "net" polarization of γ rays from both fragments is measured. In Ref. 2, the authors argue that this direction is the same as the polarization direction of the transferred angular momentum and conclude that negative-angle scattering is predominant for deep-inelastic processes. In order to determine whether there is a predominance of negative-angle scattering, the direction of the transferred angular momentum must be extracted from measured polarizations and compared to what the reaction mechanism predicts for negative- or positive-angle scattering. The polarization direction is clearly the direction of the transferred angular momentum if the fragment polarizations are in the same direction. As is shown in Table I, however, the fragments might each be completely polarized but in opposite directions, and so the measured polarization would depend upon the number of γ rays detected from each fragment. Assumptions about the decay processes in the fragments and particle-γ correlations would then be necessary to obtain the direction of the transferred angular momentum. The interpretation of negative-angle scattering then depends upon assumptions about the reaction mechanism. The less than 100% polarization observed for the deep-inelastic products in this experiment could result from contributions of positive- and negative-angle scattering, from the possibility that the fragment polarizations are opposite, from the average L being greater than $|l_i^0 - l_f^0|$, or from a reaction mechanism very different from the quasielastic one.

In conclusion, predictions of polarizations in quasielastic heavy-ion reactions are complicated

TABLE I. Polarizations for the condition $M_L = +L$. The final state of ^{15}O is assumed to be $p_{1/2}$ and the spin, J_B, of the residual nucleus is varied.

J_B	L	$P(^{15}\mathrm{O})$	$P(B)$
$s_{1/2}$	1	+	+
$d_{3/2}$	1	−	+
$d_{5/2}$	3	+	+
$p_{3/2}$	2	+	+
$g_{7/2}$	3	−	+

by the presence of mass transfer, charge transfer, and ejectile excitation. However, for these reactions the kinematic conditions determine the direction of the *transferred angular momentum* in a straightforward manner, and if the final states are known, the polarization of the residual nucleus and ejectile can be predicted. While the situation is straightforward, it is not as simple as had been proposed, and one should draw conclusions from polarization data cautiously.

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Note added.—A very recent paper[10] has reported measurements of the polarizations in the quasielastic reaction $^{16}O(^{16}O, ^{12}C)^{20}Ne$ which agree with the expectations of this Letter.

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Fragmentation of Isovector $M8$ Strength in ^{58}Ni

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Form factors were measured for transitions to levels at 7.937, 8.808, 10.19, 11.24, and 12.50 MeV and identified as $M8$ and assigned $J^\pi = 8^-$. The interpretation is given that the one-particle, one-hole component of these levels is dominantly $(g_{9/2}f_{7/2}^{-1})$ and composes most of the observable $M8$ strength, which is, however, only about 22% of simple shell-model predictions.

It is known[1] that measurements of strong magnetic multipole transitions in nuclei via inelastic electron scattering can give a direct measure of single particle-hole wave functions with the larger multipoles more uniquely determining the particle-hole configuration. Previous studies have been mostly confined to magnetic dipole and quadrupole transitions.[2] Exceptions are a few high-q experiments in which a strong $M4$ transition was found in ^{12}C[3] and ^{16}O[4] and a strong $M6$ in ^{28}Si[5] and ^{24}Mg.[6] In the p shell the dominant component of the 4^- state is an isovector one-particle, one-hole (1p-1h) "stretched" $(d_{5/2}p_{3/2}^{-1})$ configuration. In the sd shell the dominant component of the 6^- is $(f_{7/2}d_{5/2}^{-1})$. In these nuclei the "stretched" magnetic strength, corresponding to an $M4$ in p-shell nuclei and $M6$ in sd-shell nuclei, was found dominantly in one state.

The purpose of this Letter is to extend this simple interpretation to see if it remains valid for higher magnetic multipoles in medium-mass $T_z = 1$ nuclei, specifically ^{58}Ni. Here we expect the most concentrated magnetic multipole to be an $M8$ transition to an 8^- state based on the "stretched" $(g_{9/2}f_{7/2}^{-1})$ isovector configuration. Unlike the light $T_z = 0$ nuclei where $\Delta T = 1$ transitions are enhanced over $\Delta T = 0$, we further expect to observe both $T=1 \rightarrow T=1$ and $T=1 \rightarrow T=2$ transitions in ^{58}Ni. The dominant $T=1$ and $T=2$ 8^- states are predicted[7] at 9.84 and 12.75 MeV,