Spin-Spin Dependence of Total Cross Sections as an Effect of Static Nuclear Deformation

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Recently observed nuclear spin-spin dependence of total cross sections for $n_{\mathrm{pol}}+{}^{27}\mathrm{Al}_{\mathrm{pol}}$ is accounted for by coupled-channels calculations that include the effects of the static quadrupole moment of ^{27}Al, and without any spin-spin potentials. Effective spin-spin interactions, of both spherical and tensor kinds, can thus be generated by static nuclear deformation.

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The spin-spin dependence of the nucleon-nucleus and nucleus-nucleus interactions is still poorly known. In single-scattering experiments, a direct determination of nuclear spin-spin effects requires both the projectile and target to be polarized. Several experimental studies have been made of the spin-spin dependence of total cross sections for polarized neutrons incident on polarized targets,[1] and the general evidence is that it is relatively small, if at all significantly different from zero at energies where compound-nucleus effects[2] are not important. Recently, Gould *et al.*[3] reported significant spin-spin effects in careful measurements of total cross sections for polarized 5–17-MeV neutrons incident on a vector-polarized ^{27}Al target. These authors took their data as providing evidence for the existence of both real and imaginary spin-spin terms in the optical potential.

In this Letter, we investigate the effect of the static deformation of polarized target nuclei on total cross sections and total reaction cross sections for polarized neutrons. We find that this effect alone, without any spin-spin potentials, leads to spin-spin effects in total cross sections for $n_{\mathrm{pol}}+{}^{27}\mathrm{Al}_{\mathrm{pol}}$ that have the magnitudes observed by Gould *et al.*[3] The only adjustable parameter in our calculation is the quadrupole deformation of the optical potential, which is given a value that is consistent with the experimental evidence on the static quadrupole moment of ^{27}Al.[4]

A necessary condition for the occurrence of nuclear spin-spin effects is the existence of an interaction which couples the projectile and target spins together in the scattering process. Apart from an explicit spin-spin dependent term in the optical potential, arising directly from the spin-spin dependence of the nucleon-nucleon force, there could be an interaction mechanism which couples the two nuclear spins indirectly. The projectile spin-orbit interaction couples the projectile spin to the orbital motion, and there can be a transfer of orbital angular momentum to a target of spin $I>\frac{1}{2}$ with nonzero static quadrupole moment,[5] often termed as the nuclear reorientation, in elastic scattering. This mechanism can generate an effective interaction that depends on the relative orientation of the two nuclear spins. Indeed, Blair, Baker, and Sherif[6] pointed out some time ago that the observed nonzero spin-flip probabilities[7] in proton elastic scattering from nuclei with spin $I>\frac{1}{2}$ could be accounted for by a quadrupole reorientation of the target nucleus.

A calculation of scattering observables that includes the reorientation effects in elastic scattering can be done conveniently in terms of the coupled-channel formalism.[8,9] The observables of our primary interest are total cross sections for polarized projectiles incident on a polarized target. Specifying the state of polarization of the projectile beam and target by arbitrary polarization tensors $t_{kq}(s)$ and $t_{KQ}(I)$,[10] respectively, the total cross section σ_t can be written as

$$\sigma_t=\frac{4\pi}{\hat{s}\hat{I}k^2}\sum_{kqKQ}(-1)^k\hat{k}\hat{K}t_{kq}(s)t_{KQ}(I)\sum_{\lambda}\langle kKqQ|\lambda 0\rangle\sum_{Jljl'j'}(-1)^{J-I-j-l'}(2J+1)\hat{l}\hat{l}'\hat{j}\hat{j}'\langle ll'00|\lambda 0\rangle \times W(jIj'I;JK)\begin{Bmatrix} l & s & j\\ l' & s & j'\\ \lambda & k & K\end{Bmatrix}\mathrm{Im}\,T^J_{l'j',lj}. \quad (1)$$

Here, k is the wave number, s and I are the projectile and target spins, respectively, $\hat{k}=(2k+1)^{1/2}$, etc., and $T^J_{l'j',lj}$ are the elastic-scattering T-matrix elements[11] in the spin-orbit coupling scheme. The angular-momentum quantization axis is along the beam direction. This result is obtained by an extension of a formulation[8] in terms of magnetic populations to general polarization tensors. Such generalization allows for the contraction of all summations over the spin magnetic numbers. Several important points are immediately apparent from the compact formula of Eq. (1). First, as a result of parity conservation, only even values of the orbital angular-momentum transfer λ are allowed. Second, the polarization tensor projections must be opposite to each other, $q+Q=0$. Third, only polarization tensor ranks such that $k+K$ is even can contribute to the total cross section; this follows from the symmetry properties on the exchange $lj \rightarrow l'j'$, and allows one to take the imaginary part as the last term of the equation, since the terms involving the products of the polarization tensors add to real numbers for $k+K$ even.

A similarly compact formula is obtained for the total reaction cross section, σ_r, by replacing the last term of Eq. (1) with

$$\mathrm{Im}\, T^{J}_{l'j',lj} - \sum_{l''j''} T^{J*}_{l''j'',l'j'} T^{J}_{l''j'',lj}. \tag{2}$$

The total reaction cross section is thus given directly in terms of the difference between the total cross section and the total elastic cross section.

In order to obtain the elastic-scattering T-matrix elements $T^{J}_{l'j',lj}$ we used the coupled-channel code CHUCK3.[12] We performed calculations of elastic scattering of neutrons from ^{27}Al for incident neutron energies spanning the range of 2–20 MeV. Only the elastic channel, with a quadrupole reorientation coupling to the target, was taken into account explicitly in these calculations. The energy-dependent optical potential of Becchetti and Greenlees,[13] which has a Woods-Saxon parametrization and includes a real spin-orbit term, was employed. Outside the framework of folding models, it is difficult to relate unambiguously the deformation of a nucleus to that of the optical potential.[14] For this reason, the quadrupole coupling potential was obtained by taking simply the first derivative of the central part of the Becchetti-Greenlees potential. With the assumption of the rotational model, the ground state of ^{27}Al was taken as a $\mathcal{K}=I=\frac{5}{2}$ nucleus, and the intrinsic quadrupole deformation length of the potential was taken as $\delta_2=\beta_2 R=2.26$ fm, which on the rule of equal deformation lengths corresponds to a value of $Q_2=\frac{5}{14}Q_{20}=30\ e\cdot\mathrm{fm}^2$ for the static quadrupole moment of ^{27}Al. A compilation of experimental values of nuclear moments[4] quotes values in the range $Q_2=15-38\ e\cdot\mathrm{fm}^2$ for this nucleus.

The $k=K=1$ term in Eq. (1), with polarization tensors expressing vector polarizations that are parallel in a given direction, gives directly the spin-spin cross section σ_{SS} measured as half of the difference between the total cross sections for beam and target vector polarizations parallel and antiparallel in the given direction [$\sigma_{SS}=\frac{1}{2}(\sigma_{\uparrow\uparrow}-\sigma_{\uparrow\downarrow})=\sigma_{\uparrow\uparrow}-\sigma_{\mathrm{unpol}}$]. In the experiment of Gould *et al.*, the projectile beam and target were polarized in a direction perpendicular to the beam direction, and to compare our calculations with their experimental results, the projectile and target polarization tensors are rotated appropriately,[10] as our quantization axis is the beam direction. Furthermore, the results of Gould *et al.* are normalized to unity beam and target transverse polarizations, $P=1$, which translates to a nominal value $t^{T}_{10}(I)=[3I/(I+1)]^{1/2}P=(\frac{15}{7})^{1/2}$ of the vector polarization tensor in the transverse frame for an $I=\frac{5}{2}$ target nucleus.[10] In Fig. 1, the experimental values of the spin-spin cross sections of Gould *et al.* are compared with the results of our calculations. The agreement between the theory and the data can be judged as reasonably good, for both the magnitudes of the effect and the general trend of the energy dependence. The experimental point at the lowest energy is the only exception, but here compound-nucleus effects[2] may be already important. It should be stressed that we did not attempt to fit the experimental values of σ_{SS}; a larger value of the optical-potential deformation would give obviously larger values of σ_{SS}. Gould *et al.* were able to fit their data only with both real and imaginary spin-spin terms present in the optical potential, and attributed the need for an imaginary spin-spin potential to compound-nucleus processes. Figure 1 presents also the results of our calculations of total reaction cross sections for transversely vector polarized $n+{}^{27}$Al. In order to appreciate the overall relative magnitude of these spin-spin effects, one should bear in mind that the unpolarized total and total reaction cross sections are of the order of 2 and 1 b, respectively, in this energy range.

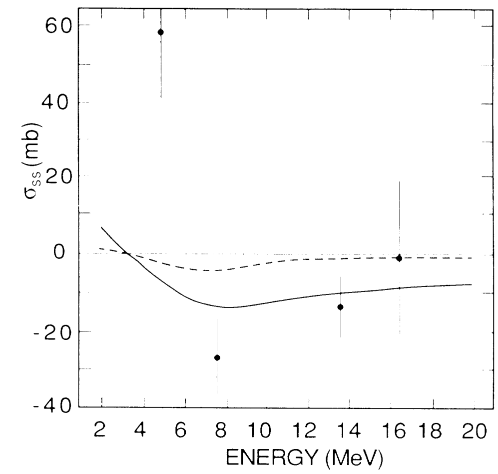

FIG. 1. Spin-spin cross sections σ_{SS} for transversely vector-polarized $n_{\mathrm{pol}}+{}^{27}\mathrm{Al}_{\mathrm{pol}}$. The solid and dashed lines are our calculations of σ_{SS} for total and total reaction cross sections, respectively. The experimental points are the measurements of Gould *et al.* (Ref. 3) of σ_{SS} for total cross sections.

Apart from considering the case of transverse polarizations, we calculated spin-spin cross sections also for longitudinal (i.e., along the beam direction) vector polarizations of the beam and target. If the effective spin-spin interaction is of the spherical type, the spin-spin effects would depend, in the absence of other spin-dependent interaction, on only the relative orientation of the two nuclear spins. A strong dependence on the orientation of each spin relative to the beam direction is an indication of the presence of a spin-spin dependence of a tensor kind.[15] Using the polarization vectors of the beam and

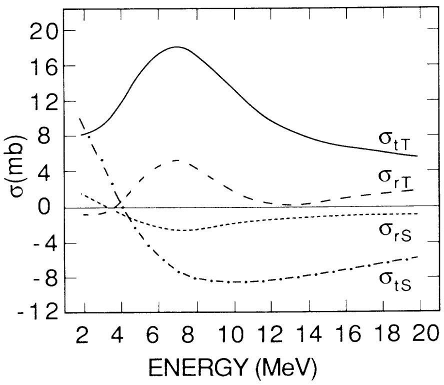

FIG. 2. Our calculations of the spherical and tensor spin-spin cross sections [see Eq. (3) in the text] for $n+{}^{27}\mathrm{Al}$. The symbols σ_{tS} and σ_{tT} denote the spherical and tensor total cross sections, respectively, while σ_{rS} and σ_{rT} denote the spherical and tensor total reaction cross sections, respectively.

target, $\mathbf{P}_s$ and $\mathbf{P}_I$, respectively, one can parametrize the spin-spin cross sections as follows

$$\sigma_{SS}=\sigma_S\mathbf{P}_s\cdot\mathbf{P}_I+\sigma_T[(\mathbf{P}_s\cdot\hat{\mathbf{r}})(\mathbf{P}_I\cdot\hat{\mathbf{r}})-\tfrac{1}{3}\mathbf{P}_s\cdot\mathbf{P}_I]. \qquad (3)$$

Here $\hat{\mathbf{r}}$ is a unit vector along the beam direction, and σ_S and σ_T can be termed as the spherical spin-spin and tensor spin-spin cross sections, respectively. Combining the results of our calculations for the transverse and longitudinal polarizations, we present our results in terms of the spherical and tensor spin-spin cross sections, σ_S and σ_T, for both the total and total reaction cross sections in Fig. 2.

In conclusion, we have shown that the recently observed spin-spin dependence in total cross sections for $n_{\mathrm{pol}}+{}^{27}\mathrm{Al}_{\mathrm{pol}}$ can be attributed to effects arising from the static deformation of the nucleus ^{27}Al. *Effective* spin-spin interactions, of both spherical and tensor kinds, can be generated by the interplay of the quadrupole nuclear reorientation and the spin-orbit force with the orbital motion. Great caution has to be exercised in deducing the existence of a direct spin-spin nucleon-nucleus force from experiments involving nuclei with static deformation.

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