Spin-Spin Potentials in $^{27}Al_{pol} + n_{pol}$ and the Nuclear Ramsauer Effect

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Spin-spin effects in neutron-nucleus interactions have been studied with a polarized ^{27}Al target and polarized neutrons of energies 5 to 17 MeV. Because of nuclear Ramsauer interference, real and imaginary spin-spin terms in the optical potential give rise to energy dependences of spin-spin effects which are out of phase. We find a central real potential $V_{SS} = 750 \pm 440$ keV, consistent with folding-model calculations, and a central volume imaginary potential $W_{SS} = -780 \pm 320$ keV, related to compound-nuclear absorption effects.

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The spin dependence of the nucleon-nucleon force is well known from scattering experiments and from studies of the properties of the deuteron. Both central and tensor terms arise in the spin-dependent potential, the central term binding the $S=1$ deuteron ground state more strongly than the $S=0$ first excited state, the tensor term leading to a D-state admixture in the deuteron ground state and a resulting nonzero quadrupole moment.

The analogous observation of spin dependence in nucleon-nucleus collisions, predicted in 1960 by Feshbach,[1] has been more difficult. Experiments with polarized ^{59}Co and low-energy ($E_n < 2$ MeV) polarized neutrons[2,3] yielded large spin-spin effects. But these results were subsequently interpreted as due to compound-nuclear effects[4,5] unrelated to the underlying spin dependence of the nucleon-nucleon force. Experiments[3] with neutrons of energies up to 30 MeV yielded much smaller effects. The values were for the most part consistent with zero effect, indicating the spin-spin potential was small. (Depolarization studies with polarized proton beams are also sensitive to spin-spin forces,[6] but interpretation of the data is reaction model dependent due to quadrupole spin flip for target spins greater than one-half.[7])

An alternate approach to the determination of spin-spin potentials was recently discussed by Mughabghab[8] who determined quite large values in ^{9}Be and ^{27}Al based on an analysis of (n,γ) slow-neutron-capture data. The interpretation was contested subsequently,[9] but nevertheless raised again the question of whether effects due to spin-spin potentials have been unambiguously observed in experiments to date.

In the present work we report measurements of spin-spin cross sections with polarized ^{27}Al and polarized neutrons of energies 5 to 17 MeV. [The spin-spin cross sections is defined as

$$\sigma_{SS} = (\sigma_p - \sigma_a)/2,$$

where σ_p (σ_a) is the total neutron cross section for neutron and target spins parallel (antiparallel).] The data provide evidence that both real and imaginary spin-spin potentials exist, and that their effects on a measurement of σ_{SS} can be distinguished by exploiting the interference phenomenon implicit in the nuclear Ramsauer effect.[10,11]

The qualitative features of this interference are apparent from Eqs. 2.89 and 2.90 of Bohr and Mottelison.[12] Compared to the wave going around the nucleus, the wave passing through the nucleus is attenuated and shifted in phase. The interference of these two waves leads to a forward scattering amplitude

$$f(0) = ikR^2(1-\alpha e^{i\beta})/2,$$

and a total cross section from the optical theorem of

$$\sigma_{tot} = 2\pi R^2(1-\alpha\cos\beta).$$

The attenuation factor $\alpha = \exp(-mWd/\hbar^2 K)$ is determined primarily by the imaginary potential W, and the phase shift $\beta = (K-k)d$ is determined by the real potential, V. Here $d \approx R$, the nuclear size, and K and k are the real wave numbers inside and outside the nucleus; $K^2 = 2m(E+V)\hbar^2$ and $k^2 = 2mE/\hbar^2$, where E is the neutron energy and m the neutron mass.

Small changes dV and dW in the real and imaginary potentials yield out-of-phase oscillations in the change in the total cross section $d\sigma_{tot}$, since $d\sigma_{tot}/dV = 0$ when $\sin\beta \approx 0$, but $d\sigma_{tot}/dW = 0$ when $\cos\beta = 0$. The oscillations due to the change in phase shift are clearly seen in the deformation-effect measurements of Marshak *et al.*[13] In our case, the changes dV and dW are due to the spin-spin potentials. A measurement of σ_{SS} performed at an energy where a change in W has no effect on σ_{tot} is sensitive only to the real spin-spin potential, and vice versa.

The experiments were performed with the Triangle Universities Nuclear Laboratory polarized-target facility[14] using transverse polarized neutrons produced in the $^2H(d_{pol},n_{pol})$ reaction. The polarized target was a 1.8-cm (thick), 1.8-cm (wide), 9-cm (high) block of ^{27}Al, cooled by a ^3He-^4He dilution refrigerator in a 7-T magnetic field. Target temperatures were typically between 11 and 14 mK, corresponding to vector polarizations of 30%–37%. The target polarization axis was parallel to the neutron polarization axis and perpendicular to the beam direction.

In our earlier measurements, time-of-flight techniques were used with pulsed deuteron beams of energies 11 and 13.8 MeV. These yielded nuetrons of energies 13.7 and 16.5 MeV in the main $^2H(d,n)^3He$ groups and average energies of 5.6 and 7.5 MeV in the neutron groups arising from deuteron breakup. Polarizations were typically 50% for the main groups and 45% in the breakup groups. The measurements at 7.5 and 13.7 MeV were subsequently repeated with a dc deuteron beam and an in-line neutron monitor in front of the polarized sample. In both cases the neutrons were detected in two liquid scintillators with light-emitting diode-stabilized photomultipliers. The results from the dc beam experiments were in agreement with those obtained from the time-of-flight data.

A measurement sequence consisted of 50 runs with the target cold followed by 50 runs with the target warm ($T \approx 1$ K). Each run consisted of four neutron-spin-left–neutron-spin-right pairs, the neutron spin being reversed by flipping the deuteron spin every 200 sec. The spin-spin cross section is given by

$$\sigma_{SS} = (\langle A_z \rangle_{cold} - \langle A_z \rangle_{warm})/\langle P_t \rangle x,$$

where $\langle A_z \rangle = \langle \varepsilon/p_n \rangle$ is the average analyzing power derived from the measured asymmetries $\varepsilon = (N_p - N_a)/(N_p + N_a)$ and neutron polarizations p_n. The neutron counts for spins parallel (antiparallel) are N_p (N_a). The average target polarization during the cold run is represented by $\langle P_t \rangle$ and $x = 0.107$ is the aluminum target thickness in atoms per barn. The warm asymmetries are typically $(20\text{–}30) \times 10^{-4}$ because of tensor-polarization effects. The dependence of the neutron yield on tensor polarization[15] produces a sensitivity to small changes in tensor polarization when the deuteron spin is flipped.

Table I summarizes the weighted average values of σ_{SS} derived in the present in the present work. We see that while the values are small, in agreement with previous measurements in ^{59}Co in the megaelectronvolt region,[3] they do differ significantly from zero at the two lower energies.

TABLE I. Spin-spin cross sections measured in the present work for transversely polarized neutrons incident on a transversely polarized ^{27}Al target. The energy spreads ΔE_n for the neutrons are based on kinematics and deuteron beam energy loss in the gas cell. The errors on σ_{SS} are determined from the standard deviations of the analyzing power data sets for each measurement.

$E_n \pm \Delta E_n$ (MeV)	σ_{SS} (mb)
5.2 ± 1.0	58 ± 17
7.6 ± 1.0	-27 ± 10
13.7 ± 0.6	-14 ± 8
16.5 ± 0.5	-1 ± 20

The total cross section is determined solely by the optical potential, independent of assumptions about the reaction mechanism. A suitable choice of real and imaginary spin-spin potentials V_{SS} and W_{SS} must be able to parametrize σ_{SS}. We consider unit-normalized central potentials of the form $(V_{SS} + iW_{SS})(\boldsymbol{\sigma} \cdot \mathbf{I})/I$, where I is the target spin and $\sigma = 2s$ for the neutron spin s.

Figure 1 shows spherical-optical-model (SOM) calculations of σ_{SS} assuming spin-spin–dependent changes in V, the central real potential, or W, the volume imaginary potential. The spin-spin cross section is given by half the difference between the total cross sections calculated for $V + V_{SS}$ and $V - V_{SS}$, or $W + W_{SS}$ and $W - W_{SS}$. The changes in Fig. 1 correspond to V_{SS} or $W_{SS} = 0.25$ MeV. The calculations were made with the energy-dependent SOM parameters of Varmer *et al.*[16] and the code ECIS.[17]

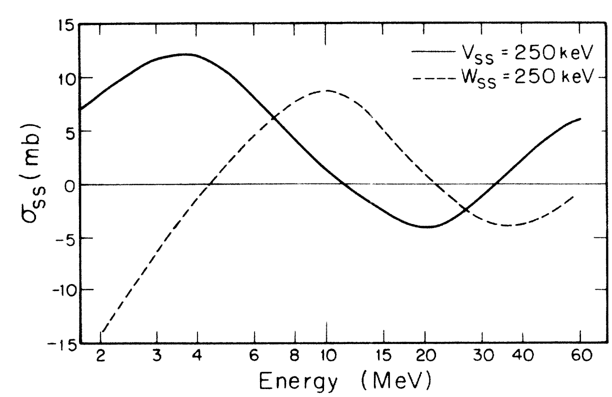

FIG. 1. Spherical-optical-model calculations of spin-spin cross sections in ^{27}Al based on assumed real and imaginary central spin-spin potentials of V_{SS} or $W_{SS} = 250$ keV. Ramsauer interference causes σ_{SS} to cross zero at different energies depending on whether the spin-spin potential is real (solid line) or imaginary (dotted line).

Simulating spin-spin effects in this manner neglects spin-orbit coupling and the contributions of tensor spin-spin forces. The effect of these terms has been considered by McAbee, Ohnishi, and Thompson[18] and is found to be small, certainly below the sensitivity of our experiments. Including these terms would not significantly change the conclusions of the present analysis.

The out-of-phase oscillations due to Ramsauer interference are clearly evident in Fig. 1 and indicate in principle how one can separately determine real and imaginary spin-spin potentials by measuring at different energies. It should be noted that all SOM parameter sets which fit the elastic scattering data lead to essentially the same zero crossing points.

Assuming V_{SS} and W_{SS} are independent of energy, the best fit to the data is shown in Fig. 2, corresponding to $V_{SS}=750\pm440$ keV, $W_{SS}=-780\pm320$ keV. The volume integrals per nucleon are 7.0 ± 4.0 and -7.6 ± 3.1 MeV fm^3, for the real and imaginary potentials, respectively. The errors are derived by varying V_{SS} or W_{SS} such that the normalized χ^2 increases by 1. The best fit assuming only a real potential ($W_{SS}=0$) is shown as the short dashed line. The long dashed line is the best fit assuming only an imaginary spin-spin potential ($V_{SS}=0$). Neither satisfactorily represents the data.

The real potential determined in the present case for ^{27}Al is somewhat smaller than the value found by Mughabghab.[8] In terms of unit normalized potentials, his volume integral per nucleons is 36 ± 18 MeV fm^3. The errors from both analyses are quite large however. Folding-model calculations of V_{SS} have recently been

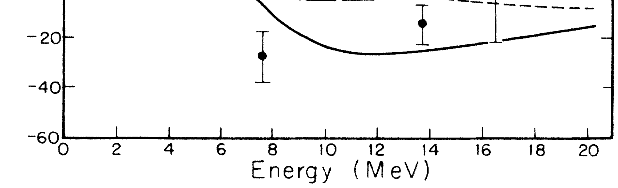

FIG. 2. Spin-spin cross sections for ^{27}Al measured in the present experiment and the best-fit prediction assuming energy independent real and imaginary spin-spin potentials of $V_{SS}=750$ keV and $W_{SS}=-780$ keV. The short dashed line is the best fit assuming only a real spin-spin potential and the long dashed line is the best fit assuming only an imaginary spin-spin potential. Neither is acceptable, indicating both real and imaginary potentials are needed to describe the data.

carried out by McAbee *et al.*[18] using realistic spin-spin interactions. Their prediction of a volume integral per nucleon of 7.9 MeV fm^3 is in excellent agreement with our measurements.

An imaginary spin-spin potential has not previously been considered explicitly. Its existence is implicit in the work of Refs. 4 and 5, where large spin-spin effects are shown to be possible because of compound-nucleus (CN) formation and the spin dependence of the nuclear level density. Since CN formation does not decrease significantly at higher neutron energies (at 14 MeV about 70% of the reaction cross section can be ascribed to CN formation) W_{SS} will likely be nonzero at all energies, not just below a few megaelectronvolts. Our value of W_{SS} predicts a spin-dependent difference in the absorption cross section of ≈ -20 mb over the energy range considered. To reproduce this value by use of the formalism of Ref. 5 requires a spin cutoff parameter of ≈ 4, somewhat larger than the value of 2.9 recently suggested by Von Egidy, Behkam, and Schmidt.[19] Exact agreement is not expected since these CN calculations are known[5] to be very sensitive to the choice of the spin cutoff parameter and also to the assumed J dependence of the partial widths (assumed independent of J in the present calculations). Nonetheless, the imaginary spin-spin potential seems likely related to CN processes and not due to any underlying spin-spin force per se.

In summary, we have shown how the Ramsauer interference phenomenon may be used to isolate real and imaginary contributions to the spin-spin potential. We find a central real potential $V_{SS}=750\pm440$ keV in good agreement with the predictions of folding-model calculations. We find an imaginary volume spin-spin potential $W_{SS}=-780\pm320$ keV, whose strength is related to compound-nuclear processes. Since W_{SS} is likely to be large even at high neutron energies, the Ramsauer interference will be important in providing a mechanism for separating its contribution from that of the small but more fundamental real potential V_{SS}. We note that a similar situation will exist in searches for parity-nonconserving (PNC) effects in neutron-nucleus longitudinal asymmetry measurements in the megaelectronvolt region. Parity mixing of CN states will lead to an imaginary PNC potential which could in principle be determined separately from the real PNC potentials, discussed for example by Avishai.[20] The largest PNC effects in neutron experiments to date have been seen in CN processes,[21] so W_{PNC} may in principle be much larger than V_{PNC}.

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