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THE NUCLEON-NUCLEUS SPIN-SPIN INTERACTION

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Abstract - We discuss the determination of the nucleon-nucleus spin-spin interaction from measurements of the depolarization parameter D in elastic proton-nucleus scattering. Recent, precise data for spin-1/2 nuclei around 70 MeV yield unambiguous evidence for spin-spin effects. The data are well described by a DWBA type calculation which includes a microscopically derived spin-spin potential. The comparison with optical model calculations indicates that spin-spin effects are not global features but depend sensitively on nuclear structure.

1 - INTRODUCTION

The fundamental nucleon-nucleon (NN) interaction contains a large and well known component which depends on the relative orientation of the spins of the two nucleons. For the nucleon-nucleus interaction the effects are expected to be much smaller, mainly due to the fact that spinflip only occurs in the interaction with the valence nucleon(s) and not with the many nucleons of the core of the nucleus. Core polarization effects, however, may change this naive picture (for a review, see /1/)

Various experimental approaches have been used to demonstrate the presence of spin-spin (SS) effects /1/: (a) transmission experiments of polarized neutrons through polarized targets (/2/ and references therein); (b) analysis of (n,γ) slow-neutron capture data /3/; and (c) measurements of the depolarization parameter D(θ) for elastic proton scattering /1,4/. The interpretation of these data was contested subsequently /1,5,6/ due to the presence of contributions from sources other than the SS interaction. The most dominant among these are compound-nucleus effects at low energy and "quadrupole spin flip" or "nuclear reorientation" effects that occur in the interaction with targets of spin > 1/2.

Recently, two precise measurements of D(θ) have been reported which avoided the above complications and allowed for a clean interpretation: elastic proton scattering from 14N at 65 MeV, measured by the Osaka group /7/, while similar data for 12C were obtained by our group at 72 MeV at PSI /8/. In the following we briefly describe the experiments and then compare the results to calculations.

2 - EXPERIMENT

In the scattering of polarized protons from a spin-1/2 target the depolarization parameter D is given by
the relationship $/9/$

$$D = \frac{p_i^\pm \cdot (1 + A \cdot p_o^\pm) - A_1}{p_o^\pm}$$

which connects the incident beam polarization $p_i^\pm$, the polarization $p_o^\pm$ of the scattered beam and the analyzing power $A_1$ with $D$. Superscripts $\pm$ refer to the sign of the incident beam polarization, the direction of which is in the y-direction, i.e. normal to the scattering plane.

Fig. 1 shows a schematic outline of the PSI experiment. The beam polarimeter POLO contained two NaI(Tl) detectors, mounted at $\pm 44.0^\circ$, which measured the left/right asymmetry in the scattering from natural carbon. The target foils ($\approx 200 \mu g/cm^2$) were always kept in the beam, thus providing a continuous sampling of the beam polarization. Beam intensity profiles, measured periodically before and after POLO, showed that the beam axis was aligned with the nominal axis to within 0.5 mm and 3 mrad.

![Figure 1: Schematic layout of the experiment, showing the polarimeters (POLO, POL2), the target ($T_1$), the Faraday Cup (FC) and the magnetic spectrometer (MSP). The inset shows POL2 in more detail: the MSP beam tube (VT) with the exit slit ($S_2$), the active targets ($AT_1, AT_2$), the telescopes ($\Delta E_L, \Delta E_R$), AT1, AT2, each 5 mm thick). Sc1 and Sc2 are the scanners used to measure the intensity profiles along the dashed lines.](image)

After passing through POLO the beam was refocussed onto the scattering target ($T_1$). The beam position on target was measured continuously by a secondary-electron-emission monitor and stabilized via feedback to steering magnets. The $^{13}C$ targets (100 - 200 mg/cm$^2$ thick) were prepared from enriched $^{13}C$, while the natural carbon targets used for normalization were cut from high-purity graphite. The beam was stopped in a shielded Faraday cup (FC), equipped with electron suppression.

Protons scattered by $T_1$ entered the magnetic spectrometer (MSP) through two Mylar windows. The spectrometer, of type QQDQQ, focussed elastically scattered protons from $T_1$ onto the two active plastic scintillator targets ($AT_1, AT_2$, each 5 mm thick) of POL2. The energy signals from either AT were added and gain-matched to the corresponding energy signals from the NaI(Tl) side detectors. For further background reduction we employed thin plastic $\Delta E$-detectors in front of the side detectors and also recorded the TOF between all detectors.

POL2 was adjustable in the horizontal plane and could be rotated ($0^\circ < \phi_2 < 180^\circ$) around the direction of the secondary beam (i.e. z'). This direction was measured with two profile scanners (Sc 1, Sc 2). The horizontal alignment of the rotation axis with the beam axis was done very carefully: profiles were measured for 'normal' ($\phi_2 = 0^\circ$) and 'reversed' ($\phi_2 = 180^\circ$) orientations and the difference of the centroids upon rotation iteratively reduced by horizontal adjustment of POL2. The centroids, measured at the beginning and at the end of each run, were found to be normally distributed about the nominal axis with FWHM's of 0.15 mm. This corresponds to an angle spread of 1 mrad FWHM.

Details about the data taking and on the formalism to extract $D$ from the asymmetries measured in POLO and POL2 can be found in /8,10,11/. The final results for $D$ are shown in Fig. 2. The data have been corrected for the effects of finite geometry ($\Delta D \leq 0.003$) and of small impurities in the $^{13}C$ targets ($\Delta D \approx 0.003$) and in the natural carbon targets of POLO ($\Delta D \leq 0.001$). The errors given represent the statistical uncertainties.
( \sim 0.003 \) with all systematic errors added in quadrature. The dominant systematic errors were due to nonproper spinflips in POL2, correlations between the polarization and the energy of the scattered beam with its position and angle at the POL2 targets and due to spectrum integration problems in POL0. The overall normalization is based on a precise calibration of \( A_y \) in p-carbon scattering at 71.2 MeV /12/ \( ( A_y = 0.8960 \pm 0.0010 ) \) and was checked by periodic measurements with a graphite target, for which \( D=1 \) on grounds of parity conservation. The average over 6 angles yielded \( D(\text{graphite}) = 1.0001 \pm 0.0012 \), with no significant dependence on angle.

The results of the Osaka experiment /7/, obtained with a very similar apparatus are shown in Fig.2 together with our microscopic prediction.

3 - CALCULATIONS

Two different approaches have been used to analyze the data (for details see /7,10/): In the first one \( D \) was fitted with an optical model (OM) potential which, in addition to the conventional parts, included real spin-spin terms of spherical (\( V_{ss} \)) and tensor (\( V_{ST} \)) type /1,13/. The parameters without spin-spin potentials were determined by a fit to \( d\sigma/d\Omega, \sigma_R, A_y \) and \( R /7,14/ \), which are insensitive to spin-spin effects. For \(^{13}C\) we found that \( D \) can be reproduced using the spherical spin-spin potential alone. Volume type form factors fit the data only for unrealistic values of the diffuseness parameter, whereas for surface type good fits were achieved with normal geometry parameters. This finding supports the naive idea of spin-spin effects as due to an interaction with the valence nucleon. The best fit with \( V_{ss} = (0.7 \pm 0.1) \) MeV is represented by the dashed curve in Fig.2. A refined OM analysis in terms of Fourier-Bessel expansions significantly improved the description of \( d\sigma/d\Omega \) and \( A_y \), but had no influence on the value of \( V_{ss} \).

Figure 2: \( D(\theta) \) for \(^{13}C\) (left) and \(^{15}N\) (right). The solid lines represent the microscopic predictions, the dashed line the conventional OM fits mentioned in the text.

For \(^{15}N /7/ \) a combination of \( V_{ss} \sim 4 \) MeV and \( V_{ST} \sim 3 \) MeV fitted the data well (Fig.2 dashed curve), although any one of the two types of potentials alone was found to give a reasonable description. In any case, these strengths appear too high in comparison to shell model calculations or other experimental studies /1/.

In the microscopic approach /10,15/ the SS independent potential \( (J=0) \) was taken from the conventional OM and the SS dependent potential \( (J=1) \) treated in DWBA. The SS potential was calculated by folding a density dependent, effective interaction over the distribution of the nucleons in the target. The effective interaction was based on the Paris NN potential. The wave functions used reproduce other valence-nucleon dependent observables such as the magnetic moment and the transverse form factor \( F_T^2 \) for elastic electron scattering. For an \( I = 1/2 \) nucleus \( F_T^2 \) is purely M1 and is therefore sensitive to the same parts of the wave function as the depolarization. Since electron scattering data are well established experimentally, we are on firm ground with respect to the nuclear structure input and can proceed to study the SS dependence. Vice versa, details of the nuclear structure show up in \( D \) just as in \( F_T^2 \) – and \( D \) could in principle be used to study nuclear structure details.

These calculations (solid curves in Fig.2) reproduce the \(^{13}C\) data well and explain qualitatively the large
effect observed for $^{16}N$: the transverse form factor $F_T$ for $^{16}N$ is about ten times larger than for $^{13}C$ /16/.
and the implicitly larger $J = 1$ contribution is reflected in a larger depolarization. The finding that the depolarization effect in $^{16}N$ is much larger than in $^{13}C$ is thus not a consequence of a stronger SS interaction, but is due to the specific nuclear structure of the $^{16}N$ ground state. The less than perfect agreement with the experiment may be due to the fact that the OM used in our calculation was obtained by extrapolation from nearby nuclei and at 72 MeV. Since the calculation of $D$ depends sensitively on the description of $d\sigma/d\Omega(J = 0)$ in the OM /10/, a direct fit to $^{16}N$ data at the correct energy is expected to improve the description of $D$.

In principle the different response for $^{13}C$ and $^{16}N$ could also be due to a difference in the strength of the SS interaction between proton-neutron and proton-proton, since $^{16}N$ is supposed to consist of a $1p_{1/2}$ proton hole in a closed shell $^{16}O$ and $^{12}C$ of a $1p_{1/2}$ neutron outside a closed $^{12}C$ core. We have therefore calculated $D$ for two other, similar cases, where the values of $F_T$ are much closer /10/: the $I=1/2^+$, $s/d$ shell nuclei $^{29}Si$ and $^{31}P$. The resulting effects in $D$ are $5 \%$ and show an enhancement of about 30% for $^{31}P$ ($2s_{1/2}$ proton hole) over $^{29}Si$ ($2s_{1/2}$ neutron). Again, this small difference is compatible with the 50% larger $F_T$ value for $^{31}P$ and thus supports the above explanation. The calculations are consistent with preliminary results of the Osaka group /17/.

Based on the preceding discussion we draw the following conclusion: The description of the interaction of the projectile with a single valence nucleon – which dominates the behaviour of $D$ – is beyond the scope of the OM. It is therefore no surprise that we find large differences in the potentials as extracted from nuclei with very different configuration. Given this situation, the concept of a SS contribution to a purely phenomenological OM potential appears to have little meaning. Only microscopic calculations taking into account details of the valence nucleon configuration can be expected to describe SS dependent observables.

REFERENCES

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