ISTITUTO NAZIONALE DI FISICA NUCLEARE

Sezione di Padova

INFN-BE-84/7
26 Luglio 1984

Revised Version
19 Novembre 1984

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NEUTRON-NUCLEUS SPIN-SPIN EFFECT IN ^{59}Co

D. Toniolo and R. Zannoni
Dipartimento di Fisica dell'Università di Padova, and
INFN - Sezione di Padova

ABSTRACT

The spin-spin cross section of ^{59}Co for neutrons is satisfactorily explained by adding the contribution of the compound-nucleus formation to the usual optical model contribution. Both effects are evaluated in the framework of coupled-channel calculation. A new evaluation of the spin-spin optical potential strength V_{ss} for the n-^{59}Co interaction has therefore been made by fitting the experimental data between 0.3 and 30.6 MeV. A values $V_{ss} = (-0.30 \pm 0.12)$ MeV has been found which is significantly different from zero.

1. - INTRODUCTION

In recent years many attempts have been made to prove experimentally the existence of a spin-spin dependent term in the nucleon-nucleus optical potential. The most simple potential of the type $U_{ss}(r) = -V_{ss} f(r)\, \bar{\sigma} \cdot \bar{I}$, where $1/2\, \bar{\sigma}$ and $\bar{I}$ are the spin operators of the nucleon and of the nucleus, respectively, and f(r) is an opportune form factor, has been suggested by Feshbach(1). The experimental measurements which have been carried out until now and through which attempts have been made to deduce the characteristic parameters of the above-mentioned potential, have been essentially of two types:

a) measurement of the depolarization of polarized nucleons scattered by unpolarized nuclei(2-6);

b) observation of the influence of the relative orientation of the neutron and nucleus spins in experiments on the transmission of polarized neutrons through polarized targets(7-17).

Of the transmission experiments, with the exception of some carried out at very low energies on some rare earths, only those on ^{59}Co have given a spin-spin cross section σ_{ss} significantly different from zero. This is defined as:

$$\sigma_{ss} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{2 p_n p_t} \qquad (1)$$

where $\sigma_{\uparrow\uparrow}$ and $\sigma_{\uparrow\downarrow}$, are the total cross sections for parallel and antiparallel spins, respectively, and p_n and p_t are the polarizations of the neutrons and the target. The most accurate measurements of this effect have been carried out by Fisher et al.[8] in the energy interval of the incident neutrons between 0.3 and 1.76 MeV, with two other points at 3.35 and 7.95 MeV, and with the spin directions parallel to the beam (parallel geometry), and by Heeringa and Postma[9] between 0.39 and 2.68 MeV with spin directions perpendicular to the beam (perpendicular geometry). Attempts to extract an univocal V_{ss} value from the above-mentioned measurements were unsuccessful in that recourse had to be made to two V_{ss} values (-2.5 MeV for $E_n < 1$ MeV, and 1.4 for $E_n > 1$ MeV) in order to fit the data. A possible explanation for this ambiguity was provided by Thompson[18], who showed that the compound nucleus mechanism could contribute significantly to this effect, especially at low energies. To overcome this difficulty in the analysis of the data, Heeringa et al.[10] carried out a transmission measurement, in perpendicular geometry, in the energy range between 8.2 and 30.6 MeV, where the effects of the compound nucleus could be retained negligible. The value of σ_{ss} thus obtained turned out to be much smaller than those obtained at lower energies, and the best-fit, which was based on a DWBA calculation, provided a value of $V_{ss} = (-0.35 \pm 0.25)$ MeV, when a form factor of the Wood-Saxon type was used in the calculation. An analogous fit provided a value of $V^t_{ss} = (-1.5 \pm 1.1)$ MeV with an analogous form factor, but with a spin-spin interaction of tensorial type:

$$U^t_{ss}(r) = - V^t_{ss}\, f(r)\, \frac{(3(\bar{\sigma} \cdot \bar{r})(\bar{I} \cdot \bar{r}) / r^2 - \bar{\sigma} \cdot \bar{I})}{2I} \qquad (2)$$

More recently, Heeringa and Postma[19], by developing Thompson's original idea[18], have shown that the data on spin-spin effect for ^{59}Co at low energy and in perpendicular geometry, can be explained in a satisfactory way even without the introduction of a spin-spin potential.

The theoretical predictions of V_{ss} give very uncertain results. Some are based on the hypothesis of polarized nuclear matter[20], while others are based on microscopic calculations in which ^{59}Co is described as being constituted by a core polarized by a proton hole in the 1f7/2 shell[21]. All these hyphotesis agree in predicting V_{ss} values of a few hundreds, or even tens, of keV, while predicting or assuming form factors of various types; the strength of a tensorial type V^t_{ss} ought to be much smaller with respect to that of the spherical potential V_{ss}.

Almost all the optical model calculations completed until now in order to obtain the spin-spin effect σ_{ss} have been based on the DWBA, on the hypothesis that the nucleus considered is of the spherical type. These calculations show that the σ_{ss} values are more or less equal in perpendicular geometry in parallel geometry, if the spin-spin potential is of the spherical type[22]. On the other hand evaluations carried out on ^{165}Ho[15], in which the rigid rotator character of the nucleus was taken into account by means of a coupled-channel calculation, have shown that the two spin-spin effects are substantially different in the two geometries. This fact led us to carry out a coupled-channel calculation of the spin-spin effect in both geometries, so that the complex structure of ^{59}Co could be taken into account. In addition to this, compound nucleus effects have also been taken into account in calculating the spin-spin effect, so that the greatest amount of experimental data could be used in the determination of one single V_{ss} value.

2. - THEORETICAL ANALYSIS

2.1. - Optical Model Coupled-Channel Calculation

The calculation which gives the optical model parameters used in reproducing the total cross section, the angular distributions and the deformation effect in the total cross section for neutrons on aligned ^{59}Co, is described in detail in Ref. (23). In that calculation, ^{59}Co is described as a spherical vibrational core (^{60}Ni) partially polarized by its coupling to a 1f7/2 proton hole (we assume that the core can contain up to a maximum of 3 quadrupole phonons of energy $\hbar\omega_2$=1.33 MeV and which have a deformation parameter β_2=0.238). A spherical spin-spin term of the type

$$U_{ss}(r) = -\frac{V_{ss}}{I} \frac{\vec{\sigma}\cdot\vec{I}}{1+\exp((r-R_o)/a)} \qquad (3)$$

was added to the optical potential used in Ref. (23).

Fig. 1 shows the resulting spin-spin effect σ_{ss} up to the energy of 60 MeV, in both geometries,

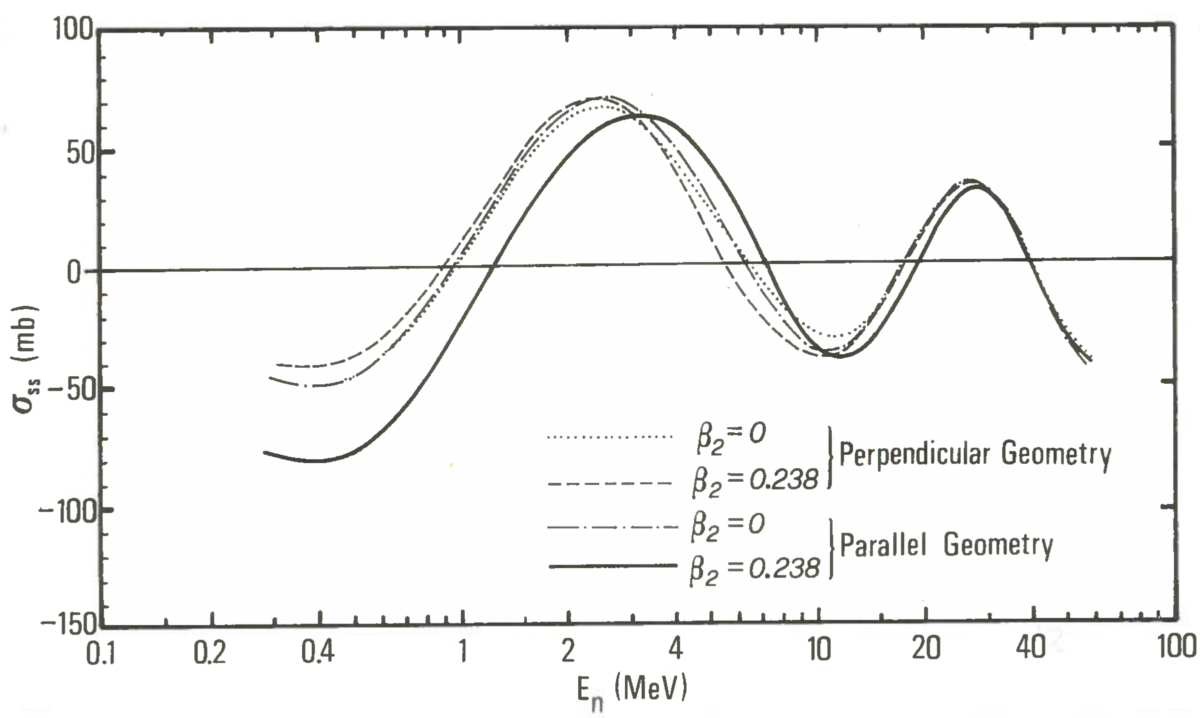

FIG. 1 - The spin-spin effect σ_{ss} versus neutron energy, calculated with V_{ss}=-0.5 MeV. The continuous line represents the result of the calculation in parallel geometry, the dashed line, that in perpendicular geometry; both the calculations were carried out with a deformation parameter β_2=0.238 (see text). The single-dotted line represents the result of the calculation in parallel geometry, and the dotted line the result obtained in perpendicular geometry; both were carried out in the absence of deformation (β_2=0).

with V_{ss}=-0.5 MeV; it also shown the curve which is obtained with the same optical model parameters when the "deformed" character of the ^{59}Co is not taken into account (β_2=0). It should be noted that, in the "non-deformed" case, the results in the perpendicular and parallel calculations practically coincide with each other, but that they differ when one takes the structure of the ^{59}Co nucleus into consideration. The calculation carried out without the inclusion of deformation produces a result similar to that one obtained by Fisher(8); the differences between the two calculations can be ascribed to the different sets of optical model parameters which have been used. It should also be noted that at the highest energies the effects in the two geometries tend to coincide with each other and with those calculated without taking deformation into account. It has been verified that, at all energies, the number of excited coupled levels has very influence on the result: the essential features of the spin-spin effect depend almost exclusively on the properties of the ground state in an analogous way to what happens for the deformation effect(23).

2.2. - The Compound-Nucleus Effect

At low neutron energies strong fluctutations in the spin-spin cross section can be observed analogous to those exhibited by the total cross section σ_t where the resonances of the compound nucleus do not yet completely overlap; furthermore, the density of levels depends on the angular momentum J of the compound nucleus(24). These facts led Thompson to suggest that the probability for the formation of the compound-nucleus states depends on the relative orientation of the spins of the neutron and the nucleus, thus giving rise to an effect which is not attributable to a spin-spin term in the optical potential. This effect gradually vanishes with the increase in energy, when the resonances increasingly overlap. Heeringa and Postma(19) have already extended Thompson's work, whose calculation was limited to s-wave only, to a greater number of waves using the transmission coefficients obtained from a spherical optical model calculation. Here, we provide a calculation in which the generalized transmission coefficients T_{ljJ}, which were introduced by Tamura(25) and which were derived from a coupled-channel calculation in order to take into account also the deformed nature of ^{59}Co, were used.

The cross section for the formation of a compound nucleus of spin J in the scattering of a polarized nucleon on a polarized nucleus can be written in the following way:

$$\sigma_{CN}^{(p_s,p_t)}(l, j, J) = \pi k^{-2}(2l+1)\, T_{ljJ}\, W_{ljJ}^{(p_s,\, p_t)} \quad . \tag{4}$$

Here, s and l represent the projectile spin and orbital angular momentum, respectively, which are coupled to give the angular momentum j, and I is the initial spin of the target nucleus; p_s and p_t denote the polarization states of the nucleon and the target, respectively. As usual, k is the wave-number of the incoming particle; by $W_{ljJ}^{(p_s,p_t)}$ we denote the probability that a state of total spin J is formed in the collision process. If the beam and the target polarizations, p_s and p_t, respectively, are described through the occupation numbers of the magnetic substates $p(m_s)$ and $p(m_t)$, this probability can be represented as follows:

$$W_{ljJ}^{(p_s,p_t)} = \sum_{M\, m_s m_t} \left[\sum_{m_j m_1 m_2} \langle j\, I\, m_j m_2 \,|\, JM \rangle \langle l\, s\, 0\, m_1 \,|\, j m_j \rangle \times \right. \tag{5}$$

$$\left. \times\; D^{s}_{m_1 m_s}(\Theta_1, \Theta_2, \Theta_3)\, D^{I}_{m_2 m_t}(\Theta'_1, \Theta'_2, \Theta'_3) \sqrt{p(m_s)\, p(m_t)} \right]^2 .$$

In this formula the rotation matrix elements

$$D^{s}_{m_1 m_s}(\Theta_1, \Theta_2, \Theta_3) \qquad \text{and} \qquad D^{I}_{m_2 m_t}(\Theta'_1, \Theta'_2, \Theta'_3)$$

for the projectile and the target, respectively occur whenever in the calculation of $p(m_s)$ and $p(m_t)$ are directions different from that of the beam chosen as quantization axes. The spin-spin cross section σ_{ss}^{CN} therefore is:

$$\sigma_{ss}^{CN} = \frac{\pi k^{-2}}{2p_s p_t} \sum_{ljJ} (2l+1)\, T_{ljJ} \left(W_{ljJ}^{(p_s,p_t)} - W_{ljJ}^{(p'_s,\, p_t)} \right) , \tag{6}$$

where p'_s indicates a state of polarization of the projectile opposite to p_s. This σ_{ss}^{CN} turns out to be nearly zero, as was to be expected, in fact, because the spin-spin potential does not contain an imaginary part.

Let us remember that in the hypothesis of separate resonances $T_{ljJ} = 2\pi \langle \Gamma_{ljJ} \rangle\, \varrho(J)$. If we assume (Ref. (18)) that the compound-nucleus spin-spin effect is to be attributed exclusively to the non-uniform distribution of the level density of the compound nucleus, and since this distribution, according to the statistical model of the nucleus, turns out to be dependent on J, by means of the formula:

$$\varrho(J) = \varrho(0)\,(2J+1)\, \exp\left(-J(J+1)/2\sigma^2\right) , \tag{7}$$

where σ is the spin cutoff parameter, we can substitute T_{ljJ} with $c\,\varrho(J) T_{ljJ}$, c being an opportune normalization constant. It can be obtained from the condition that the non-polarized cross sections which are calculated with the two series of T_{ljJ} coincide. We thus obtain

$$c = \frac{\sum_{ljJ} (2l+1) T_{ljJ} W_{ljJ}^{(0,0)}}{\sum_{ljJ} (2l+1) T_{ljJ}\, \varrho(J)\, W_{ljJ}^{(0,0)}} . \tag{8}$$

With the above modifications for the transmission coefficients, the spin-spin effect turns out to be

$$\sigma_{ss}^{CN} = \frac{\pi k^{-2}}{2p_s p_t} \sum_{ljJ} (2l+1) T_{ljJ}\, \varrho(J) \left(W_{ljJ}^{(p_s,p_t)} - W_{ljJ}^{(p'_s,p_t)} \right) \times \frac{\sum_{ljJ} (2l+1) T_{ljJ} W_{ljJ}^{(0,0)}}{\sum_{ljJ} (2l+1) T_{ljJ}\, \varrho(J)\, W_{ljJ}^{(0,0)}} . \tag{9}$$

In this expression, the spin cutoff σ is the only parameter which can be varied. The result of the calculation of σ_{ss}^{CN} versus energy for some values of this parameter is exhibited in Fig. 2. The coefficients used, T_{ljJ}, where $l < 4$, are displayed in Fig. 3; they have been calculated with V_{ss}=-0.5 MeV; however, the value of σ_{ss}^{CN} seems to depend only very slightly on V_{ss}.

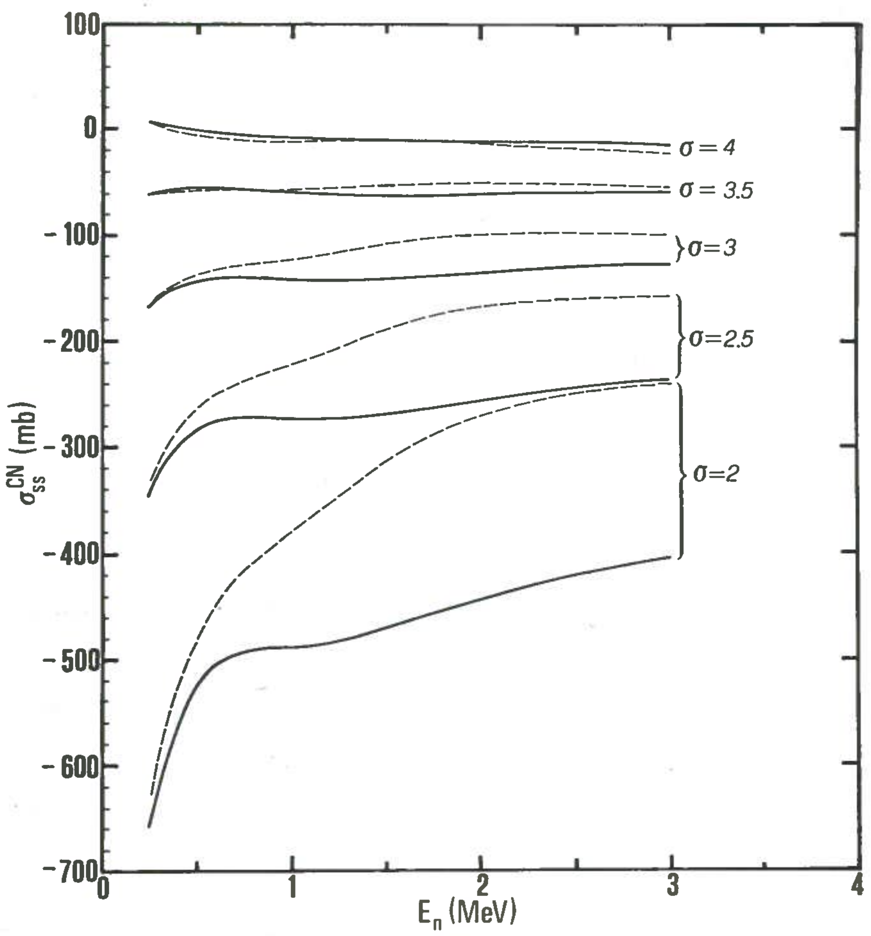

FIG. 2 - The compound-nucleus spin-spin effect versus neutron energy, calculated for several values of the spin cutoff parameter σ. The continuous lines represent the effects calculated in parallel geometry; the dashed lines represent the effects calculated in perpendicular geometry.

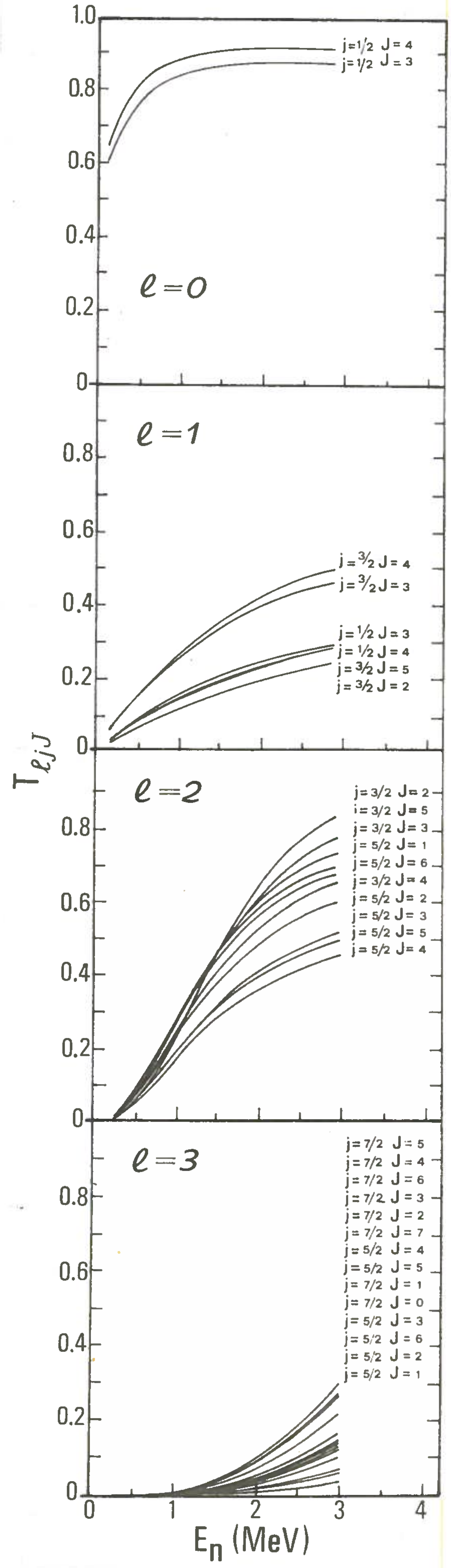

FIG. 3 - The generalized transmission coefficients T_{ljJ} used in the calculation of σ_{ss}^{CN} up to l=3 versus neutron energy; in the calculation we put V_{ss}=– 0.5 MeV.

3. - COMPARISON WITH THE EXPERIMENTAL DATA

The expression (9) for the compound-nucleus spin-spin effect is, strictly speaking, valid only in the presence of non-overlapping resonances. In the case of the interaction n-^{59}Co, we can calculate the ratio $<\Gamma>/<D>$ between the averaged width of the resonances and their average spacing following Refs. (24) and (26); thus we find that for E_n=1.75 MeV, $<\Gamma>/<D>$=1, and that for E_n=4 MeV $<\Gamma>/<D>$=15. The following criteria have therefore been followed in the analysis of the experimental data: for $E_n < 1.75$ MeV, where the compound-nucleus resonances are still isolated, the spin-spin effect has been calculated as the sum of a term which is dependent on the spin-spin optical potential part (the strength of which is V_{ss}), and of a term which is due to the compound nucleus formation and is calculated by means of Eq. (9); for $E_n > 4$ MeV, i.e. in the energy region in which the resonances are strongly overlapping, the compound-nucleus term has been omitted. In the energy interval between 1.75 and 4 MeV the resonances of the compound nucleus overlap more and more, thus causing a gradual disappearance of the compound-nucleus spin-spin effect; this change however is not easily quantifiable. Therefore the data in the energy interval between 1.75 and 2.88 MeV, taken from Fig. 1 of Ref. (9), have been left out in our analysis.

The results of the best-fit for various groupings of the experimental data are given in Table I. One can see that the various partial results are compatible with each other: in each case, the V_{ss} sign is negative; the numerical values which were obtained for V_{ss} and σ and which are relative to groups of independent data, agree well with each other once the errors have been taken into account.

TABLE I - Results of the best-fits performed on different data groups.

E_n(MeV)	Geometries	V_{ss}(MeV)	Spin cutoff σ	Correl. Coeff.
> 4	Pe + Pa	- 024 ± 0.14	----	----
< 1.75	Pe + Pa	- 0.42 ± 0.22	2.9 ± 0.1	+ 0.07
< 1.75	Pe	- 0.29 ± 0.28	2.8 ± 0.1	- 0.20
< 1.75	Pa	- 0.94 ± 0.40	3.1 ± 0.2	+ 0.46
{ < 1.75, > 4	Pe + Pa	- 0.30 ± 0.12	2.9 ± 0.1	+ 0.04

E_n= Neutron energy in laboratory system; Pe= Perpendicular geometry; Pa= Parallel geometry.

It must be emphasized that the relatively low correlation between the values of V_{ss} and σ in the fits at low energies indicates that the spin-spin effect due to the direct interaction of the spins of the neutron and the target is not completely masked by the compound-nucleus effect. Therefore it is possible to obtain some information on the strength V_{ss} of the spin-spin optical potential from the data at low energy. It should also be noted that the value 2.9 ± 0.1 for the spin cutoff parameter, obtained through the analysis of all the data, coincides with the value 2.9 obtained from other experimental data and reported in Ref. (24). The result of the best-fit, together with the other experimental data considered, is displayed in Fig. 4.

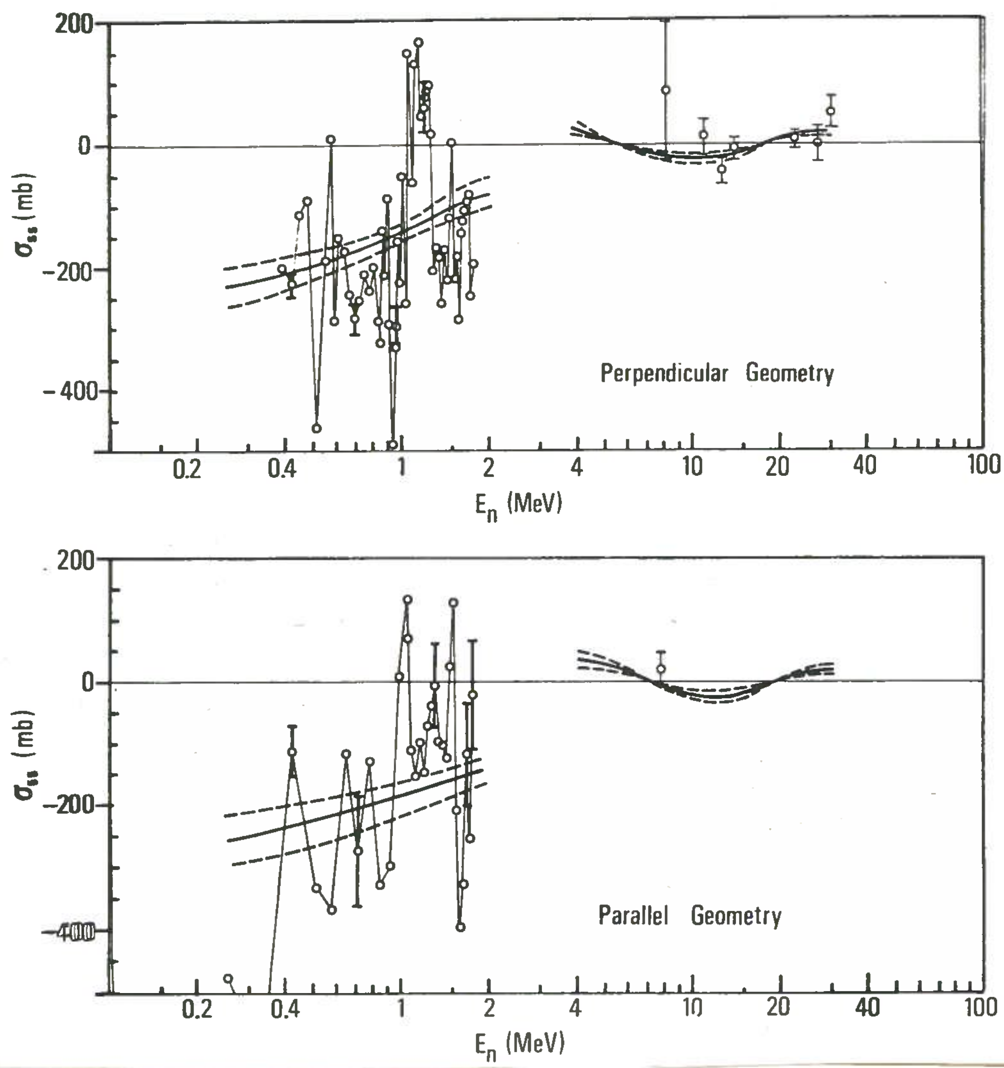

FIG. 4 - The experimental data taken from Refs. (8) and (9), together with the theoretical spin-spin cross section σ_{ss}, calculated with $V_{ss}=-0.30$ MeV and $\sigma=2.9$ (continuous lines). The dashed lines represent the upper and the lower limits due to the errors on the parameters.

4. - CONCLUSIONS

In this paper, it has been shown that all the experimental data available in the literature referring to spin-spin effect in the total cross section for n-^{59}Co scattering can be interpreted as the sum of two effects: the former is due to a spin dependent term-$V_{ss}f(r)\vec{\sigma}\cdot\vec{I}$; the latter, important for relatively low energies ($E_n < 4$ MeV), is due to the dependence of the compound-nucleus level density on the angular momentum J. The optical model contribution was obtained from a coupled-channel calculation based on a model describing ^{59}Co as a harmonic vibrational core coupled to a proton hole in a 1f7/2 shell. The effects predicted by this calculation for the perpendicular and parallel geometries, respectively, turn out to be noticeably different from each other, at least for energies less than 10 MeV; this should be ascribed substantially to the deformation of the ^{59}Co ground state. The second contribution, which depends on the statistical distribution parameter σ of the level density (the spin cutoff parameter), was calculated from the generalized transmission coefficients obtained from a coupled-channel calculation, in the energy interval where the compound-nucleus resonances are still separate.

Even though the compound-nucleus contribution turns out to be comparable with the contribution of the spin-spin term in the optical potential, and in spite of strong fluctuations in the experimental data in the energy region considered corresponding to strong fluctuations in the total cross section, it is nevertheless possible to obtain some information on the V_{ss} value, thus improving the values obtained from the high energy data only.

The available experimental data have been fitted at neutron energies greater than 4 MeV, where the compound-nucleus resonances completely overlap and the compound-nucleus effect is therefore negligible, and at energies lower than 1.75 MeV, where on the contrary the resonances are separated and the compound-nucleus effect can be calculated quite simply. We thus obtained $V_{ss}=(-0.30 \pm 0.12)$ MeV and $=2.9 \pm 0.1$. This V_{ss} value is in agreement with the one obtained by Heeringa et al.[10] using only the data obtained at high energies and in the perpendicular geometry $V_{ss}= (-0.35 \pm 0.25)$ MeV. The present result, however, is sensibly more precise and greater than the error. The present work seems therefore to confirm, consistently with the somewhat vague theoretical predictions, that the spin-spin optical potential in the n-^{59}Co interaction is repulsive with a strength of a few hundreds of keV.

ACKNOWLEDGEMENTS

The authors are indebted to Profs. U. Fasoli and G. Zago for their very kind interest, encouragement, and helpful discussions throughout the course of this work.

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