Neutron-nucleus spin-spin interaction in the low MeV range

W. Heeringa
Kernforschungszentrum Karlsruhe, Institut für Kernphysik und Teilchenphysik, 7500 Karlsruhe, Federal Republic of Germany

H. Postma
Department of Applied Physics, University of Technology, 2628 CJ Delft, The Netherlands
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An attempt is made to find a satisfactory explanation for the average spin-spin cross section of ^{59}Co for neutrons between 0.3 and 2.9 MeV. Calculations with an optical model spin-spin potential obviously fail to reproduce these data. A hybrid model is developed containing elements of compound-nucleus formation and of the optical model. Partial waves with orbital momenta up to $l=4$ are taken into account. This model yields a good explanation of the ^{59}Co data. It also agrees with the spin-spin cross section of ^{165}Ho, the only other nuclide for which data exist above 0.1 MeV.

[NUCLEAR REACTIONS Spin-spin interaction model applied to ^{59}Co, ^{165}Ho.]

I. INTRODUCTION

In this paper the spin-spin cross section observed in the neutron interaction with nuclei is discussed in terms of a hybrid model containing elements of compound nucleus formation and of the optical model. The spin-spin cross section σ_{SS} is defined as

$$\sigma_{SS}=\tfrac{1}{2}(\sigma^{\uparrow\uparrow}-\sigma^{\uparrow\downarrow}) , \tag{1}$$

where $\sigma^{\uparrow\uparrow}$ and $\sigma^{\uparrow\downarrow}$ are the total cross sections for the fully polarized beam and target in the case of parallel and antiparallel spin orientations. Spin-spin cross sections have been measured by several groups employing polarized neutron beams from a few keV's to several MeV's and polarized targets of ^{59}Co, ^{165}Ho, and some other rare earth elements.[1–13]

For ^{165}Ho the most accurate results were obtained by Fasoli *et al.*,[9] who measured σ_{SS} with neutrons with energies from 0.4 to 2.5 MeV in steps of 0.2 MeV. Other groups have also carried out experiments with this target nucleus using neutron energies of 0.4,[5,8] 1,[6,8] and 8 MeV.[7] All these data are essentially consistent with zero. For ^{165}Ho only below 0.1 MeV has a spin-spin cross section significantly different from zero been found.[10] At such low energies a few other rare earth elements have been investigated, the results of which are all consistent with zero.[11–13]

For ^{59}Co the situation is more interesting. The most detailed measurements have been carried out by Fisher *et al.*[2] with neutrons between 0.26 and 1.76 MeV (31 data points) and with the polarizations of the particles longitudinal with respect to the beam direction, and by the present authors[3] using neutrons from 0.39 to 2.88 MeV (92 data points) and polarizations perpendicular to the beam. These two different orientations will hereafter be called *longitudinal geometry* and *perpendicular geometry.*

In the observed spin-spin cross section strong fluctuations occur up to the highest energy. The energy resolution was different for each experiment, but the data agree very well when averaged over intervals of 300 keV; see Table I. The spin-spin cross section obtained is essentially negative and has an average value of about $\sigma_{SS}=-150$ mb over the whole energy range.

Spin-spin cross sections can be described by adding a spin-spin dependent term to the optical potential. Such terms were first suggested by Feshbach.[14] The simplest possibility is the spherical term

$$U_{SS}(r)=-V_{SS}f_{SS}(r)\vec{\sigma}\cdot\vec{I}/I , \tag{2}$$

where V_{SS} and $f_{SS}(r)$ denote the strength and the radial shape of the potential, $\vec{\sigma}$ is the Pauli spin of the projectile,[15] and $\vec{I}$ is the spin of the target nucleus. It is customary to employ in these expressions the Pauli spin $\vec{\sigma}$. In the remaining part of this paper we use for the spin of the projectile the quantity $\vec{s}$, where $\vec{s}=\hbar\vec{\sigma}/2$. A second form of the spin-spin potential is the tensor term

TABLE I. Averaged experimental results of the spin-spin cross section of ^{59}Co, averaged over energy intervals of about 300 keV. The original data have been grouped in such a way that the energy intervals of both data sets overlap as much as possible.

Results of Fisher *et al.*[a] Energy interval (keV)	$\langle \sigma_{SS} \rangle$ (mb)	Results of Heeringa and Postma[b] Energy interval (keV)	$\langle \sigma_{SS} \rangle$ (mb)
215–380	-530 ± 68		
383–687	-233 ± 43	366–697	-189 ± 21
672–956	-258 ± 47	681–963	-236 ± 28
947–1226	-36 ± 30	950–1217	-42 ± 14
1212–1495	-57 ± 25	1206–1504	-111 ± 17
1486–1784	-170 ± 35	1495–1788	-150 ± 20
		1777–2066	-164 ± 21
		2068–2363	-116 ± 17
		2356–2625	-96 ± 21
		2628–2889	-117 ± 25

[a]Reference 2.
[b]Reference 3.

$$U'_{SS}(r) = -V'_{SS} f'_{SS}(r) \times [3(\vec{\sigma}\cdot\vec{r})(\vec{I}\cdot\vec{r})/r^2 - \vec{\sigma}\cdot\vec{I}]/2I \ , \quad (3)$$

where V'_{SS} and $f'_{SS}(r)$ denote again the strength and the radial shape. The tensor term causes quite different spin-spin cross sections in the longitudinal geometry as compared to the perpendicular geometry.[16] With a spherical term the effects are of course the same for both geometries. It may therefore be concluded from the close agreement between the experiments that the tensor term plays no important role.

An attempt by Fisher *et al.*[2] to fit the average behavior of their data failed because the calculated curves all had a zero crossing near 1 MeV, while the data do not show this. Their fitting procedure gave values of V_{SS} (using a volume shape of the potential) of $+1.4$ MeV when the higher energy points were fitted and -2.5 MeV for the lower energy points. These values are in strong contrast to theoretical estimates of the strength, which yield values of the order of some tenths of an MeV.[17,18] This discrepancy is even larger when the data are analyzed using a surface shape for the spin-spin potential, as suggested by the theoretical evaluations. We found that with the surface shape of Ref. 17 the experimental values of V_{SS} increase by about a factor of 3, and hence become about $+4.2$ and -7.5 MeV.

We extended these optical model calculations by varying the optical parameters over a larger range than did Fisher and co-workers. We found that the zero crossing disappears when the real potential is taken deep enough. This enables a much better fit to the data. However, the size of V_{SS} needed is still too large compared to the theoretical estimates. A fit to our data yields $V_{SS}=-2.7\pm0.2$ MeV. Moreover, the real potential is probably too deep as well. Calculated differential elastic cross sections with this potential show a behavior which is too quickly oscillating as compared to the experimental data of Ref. 19. Hence, a satisfactory optical model fit to the average σ_{SS} appears to be impossible.

Considering the strong fluctuations of σ_{SS} with energy and the problems with optical model fits, it is quite reasonable to assume that the spin-spin cross section up to a few MeV has its origin in resonance effects. To avoid such resonance effects Heeringa *et al.*[4] carried out measurements with neutrons between 8.2 and 30.6 MeV (11 data points) on the same ^{59}Co target as used for the low-energy neutron experiments. The analysis of this new data yielded $V_{SS}=-1.2\pm0.8$ MeV assuming a surface shape for the spin-spin potential. Thus these higher energy data are in accordance with a smaller value of V_{SS} as compared to the low energy data. However, the statistical accuracy is too low to make a comparison with theoretical estimates.

Now we come back to the low energy data. It was found by Fisher *et al.*[2] that the size of the fluctuations in σ_{SS} can be understood by the fluctuations in the widths and spacings of the compound-nucleus levels. The remaining problem, therefore, is to explain the large negative value of the averaged experimental σ_{SS}. An onset to a solution was given by Thompson,[20] who introduced a J dependence in the compound-nucleus formation probability. He found, using only s waves, that the sign and the magnitude of the experimental data can be reproduced in this way.

In this paper we present an extended version of the work of Thompson including also higher l waves. This is necessary, because below 1 MeV p and d waves already start to contribute significantly to the cross section. The optical model is used to calculate the transmission coefficients T_l, with which the incoming partial waves are weighted. By subsequently applying Thompson's J dependence in the compound-nucleus absorption an inequality is produced in the absorption between parallel and antiparallel spin orientations. The results will be compared in this paper with the experimental data obtained for ^{59}Co (Ref. 3) and ^{165}Ho (Ref. 9).

II. THE EXTENDED COMPOUND-NUCLEUS ABSORPTION MODEL

When a particle with orbital momentum l is incident on a nucleus, the cross section for formation of a compound nucleus with spin J can be written as

$$\sigma_{\rm CN}(l,J)=\pi k^{-2}(2l+1)T_l(J)p_l(J) . \tag{4}$$

Here k is the wave number of the particle; $T_l(J)$ is the transmission coefficient; and $p_l(J)$ is the probability that a total spin $\vec{J}$ is formed from the initial spins $\vec{I}$ of the target nucleus, $\vec{s}$ of the particle, and the orbital momentum $\vec{l}$. The quantities $p_l(J)$ are built up from the occupation numbers $p(I_z)$, $p(s_z)$, and $p(m)$ of the magnetic substates in the following way:

$$p_l(J)=\sum_{I_z,s_z,m,K,K_z} p(I_z)p(s_z)p(m) \times(II_zss_z\,|\,KK_z)^2(KK_zlm\,|\,JM)^2 . \tag{5}$$

The first step is to combine the spins $\vec{I}$ and $\vec{s}$ to the channel spin $\vec{K}$, which is then added to the orbital angular momentum.

When the compound states with spin J do not overlap strongly, we may express $T_l(J)$ as

$$T_l(J)\simeq 2\pi\langle\Gamma(J)\rangle\langle\rho(J)\rangle , \tag{6}$$

where $\langle\Gamma(J)\rangle$ and $\langle\rho(J)\rangle$ are the average neutron width and average density of the states. The J dependence of T, as suggested by Thompson,[20] is based on the assumption that $\langle\Gamma\rangle$ is independent of J. This makes $T_l(J)$ directly proportional to $\langle\rho(J)\rangle$. On the other hand, in addition we assume $T_l(J)$ to be proportional to T_l, the optical model transmission coefficient for unpolarized particles. Therefore, we express $T_l(J)$ as

$$T_l(J)=C_lT_l\rho(J) , \tag{7}$$

where C_l is a normalization constant.

The J dependence of the level density is usually written as

$$\rho(J)=\rho(0)(2J+1)\exp[-J(J+1)/2\sigma^2] , \tag{8}$$

where σ is the spin cutoff parameter, which is related to the moment of inertia of the nucleus. The behavior of this expression is shown in Fig. 1. For s-wave neutrons incident on ^{59}Co ($I=\frac{7}{2}$), only $J=3$ and 4 occur. In the case of parallel spins only $J=4$ can be made, and in the antiparallel case mainly $J=3$. This produces a negative spin-spin cross section [see Eq. (1)], as the level density for $J=4$ is lower than for $J=3$. This is the same sign as that of the experimental data. Also, the size of $\sigma_{\rm SS}$, found in this way, turns out to be of the right magnitude. Higher l waves dominate the cross section above 1 MeV. They are incorporated in the derivation of $\sigma_{\rm SS}$ given here.

The $p_l(J)$'s are different for different relative spin orientations. Hence an extra index is needed to distinguish between the various cases possible. Three cases must be considered, namely $p_l^{\uparrow\uparrow}(J)$ when the neutron and the target spins are oriented parallel to each other, $p_l^{\uparrow\downarrow}(J)$ when they are antiparallel, and $p_l^{\rm unp}(J)$ when the particles are unpolarized. The compound-nucleus spin-spin cross section can now be written as

$$\begin{aligned}\sigma_{\rm SS}&=\tfrac{1}{2}(\sigma^{\uparrow\uparrow}-\sigma^{\uparrow\downarrow})\\ &=\tfrac{1}{2}\sum_{lJ}[\sigma_{\rm CN}^{\uparrow\uparrow}(l,J)-\sigma_{\rm CN}^{\uparrow\downarrow}(l,J)]\\ &=\tfrac{1}{2}\pi k^{-2}\sum_l(2l+1)\sum_J T_l(J)[p_l^{\uparrow\uparrow}(J)-p_l^{\uparrow\downarrow}(J)] .\end{aligned} \tag{9}$$

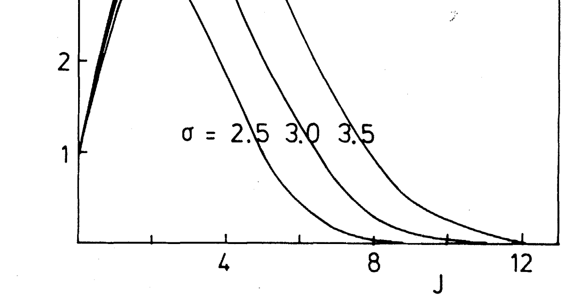

FIG. 1. The J dependence of the compound nucleus level density given by Eq. (8) for some values of the spin cutoff parameter σ.

For the total compound-nucleus cross section in the unpolarized case one obtains

$$\sigma_{CN}=\pi k^{-2}\sum_l (2l+1)\sum_J T_l(J)p_l^{\mathrm{unp}}(J)\ . \tag{10}$$

This must be consistent with the familiar expression for unpolarized particles,

$$\sigma_{CN}=\pi k^{-2}\sum_l (2l+1)T_l\ , \tag{11}$$

yielding the requirement

$$\sum_J T_l(J)p_l^{\mathrm{unp}}(J)=T_l\ . \tag{12}$$

Combining this with Eq. (7) gives the following expression for the normalization constants C_l:

$$C_l=\left[\sum_J \rho(J)p_l^{\mathrm{unp}}(J)\right]^{-1}\ . \tag{13}$$

It is advantageous here to define new normalization constants C_l', which are independent of $\rho(0)$:

$$\begin{aligned} C_l' &= C_l\rho(0) \\ &= \left\{\sum_J (2J+1)p_l^{\mathrm{unp}}(J)\right. \\ &\qquad \left.\times\exp[-J(J+1)/2\sigma^2]\right\}^{-1}\ . \end{aligned} \tag{14}$$

Now σ_{SS} can be calculated according to Eq. (9). Inserting Eqs. (7), (8), and (14) we obtain

$$\begin{aligned} \sigma_{SS}=\tfrac{1}{2}\pi k^{-2}&\sum_l (2l+1)T_lC_l' \\ &\times\sum_J (2J+1)[p_l^{\uparrow\uparrow}(J)-p_l^{\uparrow\downarrow}(J)] \\ &\times\exp[-J(J+1)/2\sigma^2]\ . \end{aligned} \tag{15}$$

With this formula we have found a hybrid expression for the spin-spin cross section. The transmission coefficients T_l are calculated using the optical model. The J dependence has been taken from the statistical model of level densities. In this expression the spin cutoff parameter σ is the only parameter that can be varied.

III. COMPARISON WITH THE ^{59}Co AND ^{165}Ho DATA

Now the experimental data will be compared with the calculations using Eq. (15). The first case to be considered is ^{59}Co. The transmission coefficients have been calculated using the optical model parameters of Guenther *et al.*[19] The results are shown in Fig. 2.

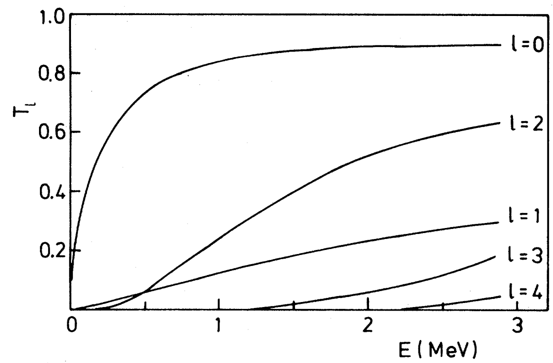

FIG. 2. Optical model transmission coefficients for neutrons on ^{59}Co.

The values of the occupation numbers $p(I_z)$ and $p(m)$, used in the calculation of $p_l(J)$ given by Eq. (5), are given in Table II. Because of rotational symmetry the magnetic quantum number of the orbital angular momentum of a beam travelling along the quantization axis is zero. This is the case in the longitudinal geometry. In the perpendicular geometry we take the quantization axis to be along the orientation direction of the particle spins. In this case the orbital angular momentum states have to be rotated through 90°, which yields

$$p(m)=\left[d_{0m}^{l}\left(\frac{\pi}{2}\right)\right]^2\ ,$$

where the d's are elements of the reduced rotation matrix. Their values have been taken from Refs. 21 and 22. The values of $p(I_z)$ follow from the temperature of the sample.[23] The neutron occupation numbers $p(s_z)$ can be expressed in the neutron polarization P_n as

$$p(\pm\tfrac{1}{2})=(1\pm P_n)/2\ .$$

In Fig. 3 curves for σ_{SS} calculated in the perpendicular geometry are shown for some values of the spin cutoff parameter σ. The curves appear to be very sensitive to σ. It is interesting to note that the higher orbital momenta cause only a slow decrease of σ_{SS} with energy. They allow for more J values to partake in the absorption, but the J values remain centered around $J=4$ in the parallel case and around $J=3$ in the antiparallel case. Thus a negative σ_{SS} is still produced because the J values involved in the antiparallel case are closer to the top of the level density curve as compared to the parallel case.

A least squares fit of the calculated curves for the perpendicular geometry to our averaged data gives $\sigma=3.1\pm0.1$. This value agrees very well with the results of the semiempirical work of Gilbert and

TABLE II. Values of the occupation numbers $p(I_z)$ of the ^{59}Co nuclei and $p(m)$ of the orbital angular momentum of the neutrons used in the calculation of σ_{SS} (perpendicular geometry).

		$l=1$		$l=2$		$l=3$		$l=4$	
I_z	$p(I_z)$	m	$p(m)$	m	$p(m)$	m	$p(m)$	m	$p(m)$
$-\frac{7}{2}$	0.057	0	0	0	$\frac{1}{4}$	0	0	0	$\frac{9}{64}$
$-\frac{5}{2}$	0.070	±1	$\frac{1}{2}$	±1	0	±1	$\frac{3}{16}$	±1	0
$-\frac{3}{2}$	0.085			±2	$\frac{3}{8}$	±2	0	±2	$\frac{10}{24}$
$-\frac{1}{2}$	0.103					±3	$\frac{5}{16}$	±3	0
$\frac{1}{2}$	0.125							±4	$\frac{35}{128}$
$\frac{3}{2}$	0.152								
$\frac{5}{2}$	0.185								
$\frac{7}{2}$	0.224								

Cameron,[24] from which the value $\sigma=3.2$ has been deduced.[25] Our calculations have revealed that there are only minor differences between σ_{SS} calculated in the perpendicular geometry and σ_{SS} in the longitudinal geometry. Hence, the data of Fisher and co-workers, taken in the longitudinal geometry, can also be explained, equally well by the model.

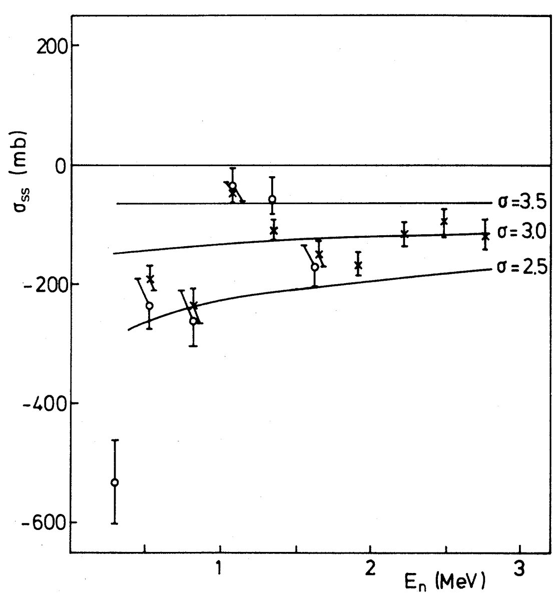

FIG. 3. Averaged values of the spin-spin cross section of ^{59}Co for neutrons measured by Fisher and co-workers (circles) and by Heeringa and Postma (crosses). The curves have been calculated using Eq. (15) for some values of the spin cutoff parameter σ.

Subsequently we compare the presented model with the ^{165}Ho data of Fasoli *et al.*[9] This is a deformed nucleus, hence part of the reaction cross section does not involve compound-nucleus states, but proceeds directly to excited levels of the ground state rotational band. The smaller compound-nucleus cross section is taken into account by using a smaller imaginary potential in the optical model. We used the parameters given by Marshak *et al.*[26] to calculate the T_l's, which are shown in Fig. 4. The neutrons and nuclei were polarized perpendicular to the beam direction; again the values for $p(m)$ from Table II have to be used. The values of $p(I_z)$ were taken from Ref. 27. In Fig. 5 calculated curves with $\sigma=4$, 4.5, and 5 are compared with the measurements. A least squares fit yields for the spin cutoff parameter the value $\sigma=4.5\pm0.1$. This is an acceptable value considering the values for σ given in the

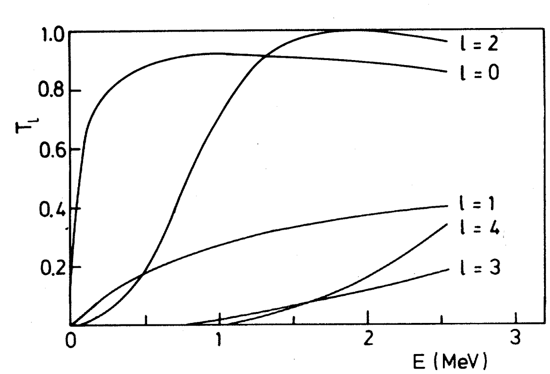

FIG. 4. Optical model transmission coefficients for neutrons on ^{165}Ho.

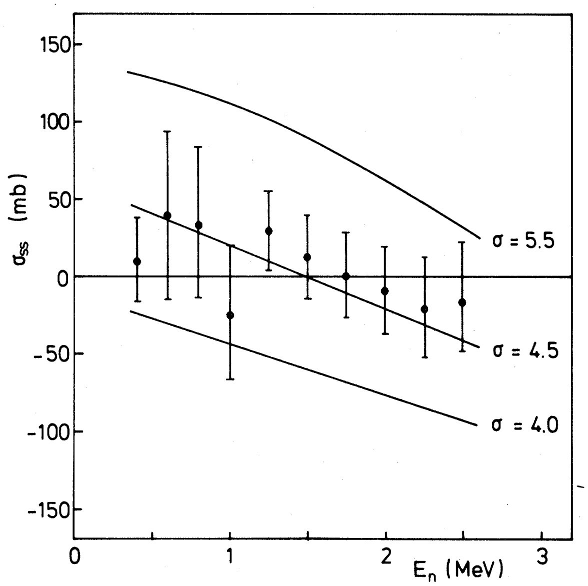

FIG. 5. Spin-spin cross sections of ^{165}Ho for neutrons measured by Fasoli and co-workers. The curves have been calculated using Eq. (15) for some values of the spin cutoff parameter σ.

literature[24,28,29] for the rare-earth elements, ranging from $\sigma=3.6\pm0.2$ found experimentally[29] for ^{180}Hf to $\sigma=5.5$ from the semiempirical work of Gilbert and Cameron.[24] Apart from the deduced size of σ it is remarkable that the trend of the data is reproduced so well by the calculated curves.

IV. DISCUSSION

The hybrid compound-nucleus absorption model presented here has been used to analyze the averaged ^{59}Co and the ^{165}Ho spin-spin cross section data. For ^{59}Co the measurements are strikingly different from zero. We have found that the optical model cannot give an acceptable explanation, whereas the proposed absorption model gives a good description. In the case of ^{165}Ho the overall data are consistent with zero. Therefore, there is no preference for one of the models. Both models can explain the small spin-spin cross sections of ^{165}Ho; in this paper with an acceptable spin cutoff parameter and in Ref. 9 with a small optical spin-spin potential.

The hybrid model may not work well in all cases. It may only apply to certain nuclides or to a certain range of nuclides. In fact, the model predicts for several nuclides relatively large differences between the strength functions S_0^+ and S_0^- for the two possible spin states $I\pm\frac{1}{2}$ for s-wave neutrons. These differences do not seem to be confirmed experimentally.[30] It can be easily demonstrated that in our model the normalized strength function difference is expressed as

$$(S_0^+ - S_0^-)/\langle S_0\rangle = 2[\rho(I+\tfrac{1}{2})-\rho(I-\tfrac{1}{2})]/[\rho(I+\tfrac{1}{2})+\rho(I-\tfrac{1}{2})] \,.$$

Thus the largest differences are expected for low spins, where the level density function is steepest (see Fig. 1). Probably the most accurate strength function differences have been measured by the Dubna group in the case of some rare earth elements.[10–13] For the nuclides with the lowest spins, ^{159}Tb ($I=\frac{3}{2}$) and ^{169}Tm ($I=\frac{1}{2}$), the average result over 2–100 keV is

$$(S_0^+ - S_0^-)/\langle S_0\rangle \leq 0.05 \,.$$

The model disagrees with this small value, predicting

$$(S_0^+ - S_0^-)/\langle S_0\rangle \simeq 1.0$$

for nuclides with spin $\frac{1}{2}$ and $\simeq 0.5$ for spin $\frac{3}{2}$.

We feel, however, that the data for specific nuclides should be extended over a larger energy range before it can be decided definitely whether the model applies. When the energy range is small, the results can be dominated by the properties of a single resonance or by intermediate structure.

We would like here to point to another phenomenon pertinent to the neutron strength function, namely the strong fluctuations that exist between the strength functions of neighboring nuclides. It has already been stated by Block and Feshbach[31] that these fluctuations have to be explained by fluctuations in the doorway state densities near the neutron binding energy. This was confirmed in later work by other authors[32–34] using different approaches to the calculation of the doorway state properties. The doorway state width is taken to be constant in this work. The situation is similar in our compound-nucleus absorption model, where the level width is also kept constant and the spin-spin cross section is originated by the variation in level density for different values of the total angular momentum J. Finally, we remark that the results of Sec. II remain unchanged when the states considered are doorway states instead of compound-nucleus states.

More experimental work is needed to investigate whether there are more nuclides with a large spin-spin cross section. This is quite feasible, because many different metallic targets can be polarized to a sufficient degree with the experimental techniques currently available.

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