Evidence for a Nucleon-Nucleus Spin-Spin Interaction in ^{9}Be

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Detailed examination of the γ-ray spectrum due to the reaction $^9\mathrm{Be}(n,\gamma)^{10}\mathrm{Be}$ reveals the presence of a spin-spin interaction of magnitude $V_{I\sigma} = 1.65 \pm 0.15$ MeV. In addition, the spectroscopic factor of the second 0^+ state at 6190 keV is determined to be $S_{dp} = 0.032 \pm 0.005$ which suggests that this state is an intruder state.

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Several experimental investigations have been carried out in search of the existence of a spin-spin interaction term in the optical model which was first suggested by Feshbach[1] some 25 years ago. To detect the effect of the spin-spin interaction various techniques have been devised which include the following: (1) transmission measurements[2-5] of polarized neutrons and targets, (2) measurement of the depolarization[6] parameter $D(\theta)$ for nucleons elastically scattered by nonzero-spin target nuclides, and (3) determination of the two spin components of the s-wave neutron strength functions and potential scattering lengths.[7,8] The main result of the experimental findings is that the spin-spin interaction term is small, except for ^{9}Be. This is in agreement with the theoretical work of Satchler.[9] The evidence for ^{9}Be comes from the analysis[6] of the depolarization data for proton-nucleus scattering of 20 and 50 MeV in terms of the optical model which revealed that the spin-dependent potential for ^{9}Be [$V_{I\sigma}(\text{surface}) = 5.8^{+0.6}_{-0.8}$ MeV] is significantly larger than that for ^{27}Al, ^{59}Co, and ^{165}Ho. However, some ambiguity may exist in the interpretation of the depolarization data as a result of the fact that departures of $D(\theta)$ from unity can be accounted for in terms of a quadrupole spin-flip effect.[10] Therefore the results from the depolarization data have to be considered as upper limits.

In the present study, I report on evidence for a nucleon-nucleus spin-spin interaction in the $n + {}^9$Be system based on a different approach. Generally, polarized neutrons and polarized targets are required in order to separate the components corresponding to spins $I \pm \frac{1}{2}$, where I is the spin of the target nucleus. However, because of certain specific nuclear properties of the final states of ^{10}Be, this limitation was circumvented. Detailed examination of the gamma-ray spectrum due to capture of thermal neutrons by ^{9}Be in the framework of the direct capture mechanism revealed that the interaction radius is spin dependent.

I first present a generalized expression for the direct capture cross section for $E1$ transitions due to capture of thermal neutrons by target nuclides with nonzero spin and then carry out a comparison of the theoretical values with the measured partial capture cross sections for the reaction $^9\mathrm{Be}(n,\gamma)^{10}\mathrm{Be}$.

It can be easily shown[8] that the direct capture cross section due to capture of an s-wave neutron by a target of spin I which undergoes a transition to a p final state is given by

$$\sigma_{\gamma f} = \sum_i \sigma_{if} S_{if}^2, \tag{1}$$

$$S_{if}^2 = (2J_i+1)(2J_f+1)\left[2\begin{Bmatrix} \frac{3}{2} & \frac{1}{2} & 1 \\ J_i & J_f & I \end{Bmatrix} S_{3/2} - \sqrt{2}\begin{Bmatrix} \frac{1}{2} & \frac{1}{2} & 1 \\ J_i & J_f & I \end{Bmatrix} S_{1/2}\right]^2, \tag{2}$$

$$\sigma_{if} = \frac{0.062}{R\sqrt{E_n}}\left(\frac{Z}{A}\right)^2 \frac{y_f^2}{6(2I+1)}\left(\frac{y_f+3}{y_f+1}\right)^2\left[1 + \frac{R_i - a_{si}}{R_i} y_f \frac{y_f+2}{y_f+3}\right]^2, \tag{3}$$

$$y_f^2 = 2mE_\gamma R_i^2/\hbar^2, \tag{4}$$

where $S_{3/2}$ and $S_{1/2}$ are respectively the $P_{3/2}$ and $P_{1/2}$ (d,p) spectroscopic amplitudes of the final states, J_i and J_f are the initial and final spins, respectively, R_i is the interaction radius, and a_{si} is the coherent scattering length. The summation is carried out over the two channel spins $i = I + \frac{1}{2}$ and $I - \frac{1}{2}$ which will later be designated by the plus and minus signs, respectively. It may be noted that Eq. (2) is proportional to the transformation of the spectroscopic factor from jj to LS coupling (channel-spin representation). In previous studies[11-13] it was demonstrated that Eqs. (2)-(4) are remarkably successful in accounting for the γ-ray spectra of nuclides in the mass regions around $A = 40$ and 140 as well as for ^{12}C and ^{13}C.

S-wave neutron capture by ^{9}Be with ground-state

TABLE I. The results of the analysis of the reaction $^9Be(n,\gamma)^{10}Be$. The (d,p) spectroscopic amplitudes and their phases for the transfer of $P_{3/2}$ and $P_{1/2}$ neutrons to ^9Be are indicated in columns 5 and 6. The spectroscopic factors for channel-spins 2 and 1 are included in columns 7 and 8, respectively.

E_γ (keV)	E_x (keV)	J^π	S_{dp}	$S_{3/2}$	$S_{1/2}$	$S_{dp}(2)$	$S_{dp}(1)$	$\sigma_{\gamma f}$ [d] (mb)
6809	0	0^+	2.1 [a]	1.45 [a]	...		2.1	4.9 ±0.5
3444	3368	2^+	0.35 [a]	−0.477	+0.350	0.342	0.008	0.86 ±0.08
853	5959	2^+	0.788 [b]	−0.436	−0.773	0.057	0.731	2.0 ±0.2
632	6180	0^+	0.031 [c]	0.176 [c]	...		0.031 [c]	0.018 ±0.003

[a]Reference 14.
[b]Reference 15 (BME potential).
[c]Present work.
[d]Reference 16.

spin and parity $J^\pi = \frac{3}{2}^-$ results in 1^- and 2^- capturing states. In the ^{10}Be system, the 0^+ states, which comprise the ground state and the excited state at 6180 keV, can be populated only from the 1^- capturing state while the 2^+ final states at 3368 and 5959 keV can be reached from both 1^- and 2^- capturing states in certain proportions determined by the values of a_{si}, $S_{1/2}$ and $S_{3/2}$, and their phases. To carry out the calculations via Eqs. (1)–(4), the scattering lengths a_+ and a_- and the $S_{3/2}$ and $S_{1/2}$ amplitudes and their associated phases are required.

Because of the good agreement between the experimental values of Darden, Murillo, and Sen[14] and the theoretical work of Cohen and Kurath,[15] the experimental values of $S_{3/2}$ and $S_{1/2}$ for the resolved states corresponding to the ground state and the excited state at 3368 keV are adopted. However, since the 5959 keV state ($l=1$) is not resolved from the 5961 keV state ($l=0$), the theoretical values are considered. All phases indicated in Table I are due to the work of Cohen and Kurath.[15] Also listed in Table I are the γ-ray energies, the corresponding excited states of ^{10}Be populated by $E1$ transitions, their spins and parities, and the experimental partial capture cross sections. The latter were measured by Jurney[16] with a Ge(Li) detector relative to the accurately known capture cross section of hydrogen. Information on a_+ and a_- can be derived from the value of the bound coherent scattering length ($b = 7.778 \pm 0.003$ fm) and the incoherent scattering cross section. Only an upper limit of 4 mb is reported[17] for the latter because of a possible hydrogen impurity in the ^9Be sample which had not been chemically analyzed. Therefore three possible cases, indicated in Table II, are considered.

In Fig. 1, I illustrate the case for which $a_+ = a_-$, i.e., $\sigma_{in} = 0$. The variations of the calculated partial capture cross sections $\sigma_{\gamma f}$ versus the interaction radius R_i for $E1$ transitions populating the ground state (0^+) and the 2^+ excited states at 3368 and 5959 keV are shown in Fig. 1. Also indicated by solid circles are the measured partial capture cross sections. As is evident, the partial capture cross sections for the ground state and the excited state at 5959 keV can be satisfied by the same value $R_i = 3.60 \pm 0.07$ fm while different values $R_i = 2.48 \pm 0.07$ fm or 4.80 ± 0.07 fm are required for the other 2^- state at 3368 keV. It may be noted from Fig. 1 that for $R_i = 3.60 \pm 0.07$ fm, $\sigma_{\gamma f}$ for the 3368 keV state is negligibly small and no reasonable change in the value of the spectroscopic amplitudes of this state can bring agreement between the calculated and the experimental value. Examination of Table I shows that in the channel-spin representation, the spectroscopic factors for the ground state and the excited state at 5959 keV are dominated by channel-spin 1 while on the other hand that of the 3368-keV state is mainly due to channel-spin 2. Therefore, the present results can be interpreted in terms of a spin dependence of the interaction radius which can be attributed to a spin-spin interaction. Note that $R_- - R_+ = +1.12$ or -1.28 fm for the two possible

TABLE II. The spin-spin potential required to fit the spin-dependent interaction radii.

Case	a_+ (fm)	a_- (fm)	R_+ (fm)	R_- (fm)	$V_{l\sigma}$ (MeV)
1	7.01 ±0.01	7.01 ±0.01	2.48 ±0.09	3.60 ±0.09	1.65 ±0.15
2	7.14	6.80	2.64	3.39	1.00
3	6.88	7.22	2.28	3.85	2.75

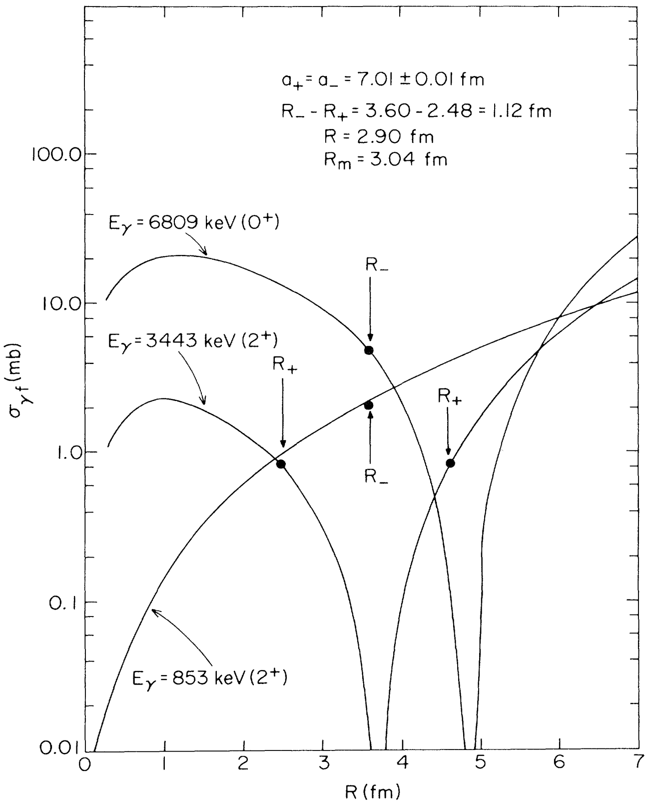

FIG. 1. The theoretical partial capture cross section vs the interactions radius for three indicated $E1$ transitions in the reaction $^9Be(n,\gamma)^{10}Be$. The solid circles denote the measured partial capture cross sections while the arrows indicate the values of the interaction radii required to fit the data.

values of R_+. Additional evidence for the spin dependence of the interaction radius can be derived from the ^9Be polarization data of Firk *et al.*[18] From the reported parameters of the bound levels and the fact that $a_+ = a_-$, one obtains $R_- - R_+ = 1.2$ fm which is in excellent agreement with our value of 1.12 fm for the case when $R_+ = 2.55 \pm 0.06$ fm. With this value of R_+ one then obtains a value of $R = 2.90 \pm 0.07$ fm by weighting by the statistical spin factors.

It is of interest to derive the magnitude of the spin-spin potential from the present results by including an additional term of the form $V_{I\sigma}\mathbf{I}\cdot\boldsymbol{\sigma}$ in the optical model potential. To compare with the results of Batty,[6] this spin-spin term was included in the real part of the optical potential. Spherical optical model calculations were carried out with the potential parameters of Ref. 8 which indicate that $V_{I\sigma} = 1.65 \pm 0.15$ MeV is required to fit the present data. The results of the analysis for the other two cases are summarized in Table II.

Since the (d,p) spectroscopic factor for the 0^+ state at $E_x = 6190$ keV is not measured, a value of $S_{dp} = 0.032 \pm 0.005$ is derived from the measured partial capture cross section. Because the energy of this state is 4.9 MeV lower than the second 0^+ excited state predicted by Cohen and Kurath,[15] I suggest that this is possibly an intruder state.

Supportive evidence for the spin-spin interaction can also be found from the study of the reaction $^{27}Al(n_{pol},\gamma)^{28}Al$. The results of a similar detailed analysis revealed that $R_+ = 4.82 \pm 0.11$ fm and $R_- = 4.52 \pm 0.05$ fm for ^{27}Al, from which a spin-spin strength of 1.2 ± 0.6 MeV was derived. It is important to note that the sign of the quantity $R_+ - R_-$ for ^{27}Al is opposite to that of ^9Be, a situation which is predicted by the optical model.

In conclusion, a detailed examination of the γ-ray spectra due to capture of thermal neutrons by ^9Be and ^{27}Al is interpreted in terms of a spin dependence of the interaction radius which can be accounted for in terms of spin-spin interactions of magnitudes $V_{I\sigma} = 1.65 \pm 0.15$ MeV and 1.2 ± 0.6 MeV, respectively.

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