MASTER

Measurement of Pair Interactions in Neodymium Ethyl Sulfate*

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ABSTRACT

The EPR spectrum of single ions of Nd^{143} in a crystal of Neodymium Ethyl Sulfate, predominantly of isotope Nd^{142} , was observed under condition of very high Boltzmann factor, i.e., high fields and low temperatures. It was found that the interactions with neighboring ions displaced the hyperfine lines from uniform spacing, and that by measuring the deviation it was possible to find the nearest neighbor interaction. The departure from a purely magnetic dipolar interaction is smaller than previous measurements would indicate. We found for the interaction Hamiltonian

$$H_{\text{int}} = K_0 \vec{S}_i \cdot \vec{S}_j + K_1 S_i^z S_j^z,$$

with

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$$K_0 = + 0.503 \pm 0.005 \times 10^{-2} \text{ cm}^{-1}$$

$$K_1 = - 3.58 \pm 0.03 \times 10^{-2} \text{ cm}^{-1}$$

$$K_0(\text{non-dipolar}) = - 0.039 \pm 0.005 \times 10^{-2} \text{ cm}^{-1}$$

$$K_1(\text{non-dipolar}) = + 0.12 \pm 0.03 \times \text{cm}^{-1} .$$

We conclude that EPR resonance at large values of H/T in magnetically concentrated crystals can yield accurate values of spin-spin interactions.

I. Introduction

Much work has been done recently on the measurement of interactions between pairs of rare-earth ions in several crystal lattices.¹ These measurements involve substituting a small fraction of paramagnetic rare earth ions into a diamagnetic host crystal and observing the paramagnetic resonance of the single ions and occasional pairs of magnetic ions. The pair interaction shifts the pair resonance from the single-ion resonance, so by measuring these shifts, one can extract the interaction energy. Unfortunately, these measurements in dilute host crystals are not ideal, for what one would like to know is the interaction between ion pairs in a magnetically concentrated crystal, so comparisons could be made between the measured interactions and the observed bulk properties of the material, e.g., heat capacity, susceptibility, transition temperatures, etc. The measurement of isolated pairs may give different results since the diamagnetic host lattice constants will in general be different from the magnetic material, and the pair may introduce a local strain. The resulting distortion of the local symmetry may break the symmetry of the interaction, and the

different pair separation will affect its magnitude. To eliminate these problems, one would like to study the pure magnetic material itself, but the problem of linewidths in a magnetically concentrated sample makes this difficult. If the measurement is done with extremely high Boltzmann factor, as reported here, the lines are sharp, but a pair measurement gives the total interaction with all the neighbors. The diagonal terms of the interaction Hamiltonian can be accounted for approximately, but if all spins are identical, the off-diagonal terms cannot be handled in perturbation theory. We have been able to circumvent this problem by studying the resonance of a small fraction of an isotope with hyperfine structure in a crystal predominately of an isotope with no nuclear spin. We found that the neighbor interactions mix with the hyperfine energy in the diagonalization of the interaction Hamiltonian, giving a departure from uniform spacing of the hfs lines; these deviations are related to the pair interactions.

II. Crystal

The ethyl sulfate (ES) lattice has been used for much of the work done on the rare earths because of the convenient crystal structure.² The rare earth positions are shown in Fig. 1. Each ion has two nearest neighbors along the crystalline c-axis at about $7 \text{ \AA}$. The six next-nearest neighbors lie about $8.7 \text{ \AA}$ away at an angle of about 66.4° from the c-axis, such that their dipolar field at the central site is much smaller than that of the nearest neighbors. The predominant interaction of the two nearest-neighbors gives the triplet structure seen by Bleaney, Elliott and Scovil³ in pure NdES. Svare and Seidel⁴ studied the temperature dependence of this triplet structure and were able to extract

the nearest-neighbor interactions from the linewidths and shifts. They found a predominately magnetic dipolar interaction with a small non-dipolar contribution. Baker⁵ studied the interaction of diluted pairs of Nd in LaES and YES and was able to get more accurate measurements because of the sharper lines, and found good agreement with the work of Svare and Seidel.

III. Experimental

The measurements described here were made with a millimeter-wave ³He spectrometer, at a frequency of 75 GHz and a temperature T of approximately 0.5°K. Under these conditions, the sample magnetization deviates less than 0.1% from its low-temperature limit. The Van Vleck linewidth, normally a few hundred gauss in concentrated crystals, is extremely narrowed in our case because the local fields are all very well defined, since essentially all the ions are polarized along the magnetic field direction. The linewidths observed are essentially the same as those of dilute ions, so the accuracy of measurement is as great.

The microwave system consists of an oversized circular waveguide "light pipe" and a germanium bolometer detector. The system is completely broad-band, and will operate from the waveguide cutoff at about $\lambda \approx 8$ mm up into the infrared. The samples are spheres of about .015" to .020" diameter, which are ground and polished in a tumbler driven by an air jet. We found that such small samples were necessary to minimize magnetostatic mode complications. The sample is mounted in the light pipe on a Mylar film and can be rotated by means of a worm-driven gear. The sample sits directly in the ³He liquid: no heating effects have been observed at the microwave power levels used, although the resonance is quite strong.

The field H , derived from a sixth order end corrected superconducting solenoid, is measured by observing the ^3He nuclear resonance with a broad band NMR spectrometer and a specially constructed non-resonant broadband coil structure. With this system, the field can be measured continuously at fields between 5 and 50 KG.

IV. Theory

We will consider the states of a single Nd^{143} ion with $I = \frac{7}{2}$ imbedded in a sea of Nd^{142} ions with $I = 0$. Except for the hyperfine term, the ions would be identical. Since the experiment is performed at very low temperature, we consider only the ground state and the first excited states of the electronic system.

The single ion Hamiltonian for the Nd^{143} is

$$\mathcal{H} = \beta[g_{\parallel}H^zS^z + g_{\perp}(H^xS^x + H^yS^y)] + A I^z S^z + B(I^x S^x + I^y S^y) \quad (1)$$

The axially symmetry g -factor and hyperfine interaction reflect the axial symmetry of the Nd site. For the $I = 0$ ions, the same Hamiltonian applies, with $A=B=0$.

For a nearest-neighbor pairs the most general interaction Hamiltonian with axial symmetry can be written as

$$\mathcal{H}_{ij} = K_0 \vec{S}_i \cdot \vec{S}_j + K_1 S_i^z S_j^z, \quad (2)$$

where it is understood that this represents dipolar plus non-dipolar contributions. We will account approximately for second-nearest neighbors by putting in only their calculated dipolar interaction in perturbation theory,

since we expect that non-dipolar contributions will be negligible. We expect that the effect of neighbors further than second will be much less, since the dipolar field drops off as r^{-3} .

A. First take the case $H \parallel z \parallel c$ axis, and $g = g_{\parallel}$

To diagonalize the nearest-neighbor problem exactly, we consider five spins in a line, i.e., a Nd^{143} spin S_3 , with Nd^{142} spins S_2 and S_4 above and below on the hexad axis; and the topmost and bottommost spins S_1 and S_5 , always up. We write the states of the system

$$|S_3^z I_3^z\rangle |S_2^z S_4^z\rangle |S_1^z S_5^z\rangle$$

and choose as basis functions the states

$$\begin{aligned} |a\rangle &= |+,M\rangle |++\rangle |++\rangle & |e\rangle &= |-,M\rangle |++\rangle |++\rangle \\ |b\rangle &= |+,M\rangle |S\rangle |++\rangle & |f\rangle &= |-,M\rangle |S\rangle |++\rangle \\ |c\rangle &= |+,M\rangle |A\rangle |++\rangle & |g\rangle &= |-,M\rangle |A\rangle |++\rangle \\ |d\rangle &= |+,M\rangle |--\rangle |++\rangle & |h\rangle &= |-,M\rangle |--\rangle |++\rangle \end{aligned} \quad (3)$$

$$\text{where } |S\rangle \equiv \frac{|+-\rangle + |-+\rangle}{\sqrt{2}} \text{ and } |A\rangle \equiv \frac{|+-\rangle - |-+\rangle}{\sqrt{2}}, \text{ and } M \equiv I_3^z \quad (4)$$

We assume that all other spins in the crystal are up, and consider these fine spins on a line to get the correct nearest-neighbor energy. Fig. 2 shows the above five-spin states. Note that states $|b\rangle$, $|c\rangle$, and $|e\rangle$ each consist of a single spin down and are therefore equal in energy,

Figure 2

except for the hfs term. Likewise, $|f\rangle$ and $|g\rangle$ have two adjacent spins down, and have the same energy. Noting that equation (2) reduces to $(K_0/2) \times (S_i^+ S_j^- + S_i^- S_j^+) + (K_0 + K_1) S_i^z S_j^z$, the diagonal matrix elements of the Hamiltonian operators equations (1) and (2) on the basis states equation (3), and readily found to be those in Fig. 3. The off diagonal terms shown come from the mutual spin flip terms $(S_i^+ S_j^- + S_i^- S_j^+)$.

We next take into account three smaller interactions, each of order 10^{-4} cm^{-1} , by calculating the shifts to second order perturbation theory and adding this correction to the diagonal terms of Fig. 3. First, we apply perturbation theory to the single-ion Hamiltonian of Nd^{143} spin S_3 , to find that the B term in equation (1) shifts the states $|+,M\rangle$ i.e., $|a\rangle$, $|b\rangle$, $|c\rangle$ and $|d\rangle$, by an amount

$$b = - \frac{B^2 [I(I+1) - M(M+1)]}{4 g \beta H} \quad (5)$$

and the states $|-,M\rangle$ by an amount

$$b' = \frac{B^2 [I(I+1) - M(M-1)]}{4 g \beta H} \quad (6)$$

The dipolar interaction with the six next-nearest neighbors, all assumed up, gives a diagonal term

$$H_{\text{diag}} = \sum_{i,j} \frac{g_{\parallel}^2 \beta^2}{r_{ij}^3} (1 - 3 \cos^2 \theta_{ij}) S_i^z S_j^z = \sum_{i,j} F_{ij} S_i^z S_j^z \quad (7)$$

where r_{ij} is the distance between ion i and j and θ_{ij} is the angle between the pair axis and the crystalline c axis. In summing equation (7) we sum i over the five spins in, say, state $|a\rangle$, etc. in Fig. 2. Then we sum j over the six next nearest neighbors of each spin i ; this latter sum is always 3, since all spins are assumed up. Etc. for $|b\rangle$,

The most important off-diagonal dipolar term is the energy-consuming mutual spin-flip term

$$H_{\text{ff}} = \sum_{j=i}^6 - \frac{\beta^2 g_{\perp}^2}{4r_{ij}^3} (1 - 3 \cos^2 \theta_{ij}) (S_i^+ S_j^- + S_i^- S_j^+) \quad (8)$$

which couples the state $|e\rangle$ with $|S'\rangle$, the totally symmetric combination of all states with one next-nearest neighbors flipped down, while the central ion is up. The energy denominator is $-AM$ and the contribution to $|e\rangle$ is

$$D = - \frac{|\langle e | H_{\text{ff}} | S' \rangle|^2}{AM} \quad (9)$$

If we apply equation (8) to state $|b\rangle$, we find the same matrix element as in the case of $|e\rangle$, but in this case the energy difference vanishes, so we cannot use perturbation theory. The proper approach would be to first diagonalize the nearest-neighbor Hamiltonian (equation (10) without the D term) then use perturbation theory on the mixed state of $|e\rangle$ and $|b\rangle$, with a well defined energy denominator. However, we find that if the off-diagonal

nearest-neighbor terms are not too large, we get essentially the same result by applying the perturbation only to state $|e\rangle$, before diagonalization. For large Boltzmann factors, we need consider only transitions from the ground state $|a\rangle$ to the excited state $|e\rangle$ of the $I = \frac{7}{2}$ ions, so we consider only terms which couple to these states. We note that $|a\rangle$ has no non-diagonal terms while $|e\rangle$ is coupled to $|b\rangle$. We now apply our perturbation, equations (5,6,7 and 8) to the $|a\rangle$, $|b\rangle$ and $|e\rangle$ terms of the matrix of Fig. 3. We do this before diagonalization, since that's easier than applying them to mixed states after diagonalization.

$$\begin{array}{c}
 |a\rangle \quad |b\rangle \quad |e\rangle \\
 \begin{pmatrix}
 |a\rangle \left(\frac{5g\beta H}{2} + \frac{AM}{2} + K_0 + K_1 + b + \frac{15}{2} F \right. \\
 |b\rangle \left(\frac{3g\beta H}{2} + \frac{AM}{2} + b + \frac{9}{2} F \quad \frac{K_0}{\sqrt{2}} \right. \\
 |e\rangle \left(\frac{K_0}{\sqrt{2}} \quad \frac{3g\beta H}{2} - \frac{AM}{2} + b' + \frac{9}{2} F + D \right)
 \end{pmatrix}
 \end{array} \quad (10)$$

Since we are interested in the energy difference between $|a\rangle$ and $|e\rangle$, and $|a\rangle$ has no off-diagonal matrix elements, we can subtract the energy of $|a\rangle$ from the diagonal and get the secular determinant for the energy difference $h\nu$:

$$\begin{array}{c}
 b \\
 e
 \end{array}
 \begin{vmatrix}
 -g\beta H - (K_0 + K_1) - 3F - h\nu & \frac{K_0}{\sqrt{2}} \\
 \frac{K_0}{\sqrt{2}} & -g\beta H - AM - (K_0 + K_1) + D + E - 3F - h\nu
 \end{vmatrix} = 0 \quad (11)$$

where $E \equiv b' - b$. The solutions are

$$-g\beta H = h\nu + \frac{AM}{2} + (K_0 + K_1) - \frac{D}{2} - \frac{E}{2} + 3F \pm \left[\left(\frac{AM}{2} - \frac{D}{2} - \frac{E}{2} \right)^2 + \frac{K_0^2}{2} \right]^{\frac{1}{2}} \quad (12)$$

where

$$D = - \left\{ - \frac{g_{\perp}^2 \beta^2}{4r^3} (1 - 3\cos^2\theta) \times \sqrt{6} \right\} / AM \quad (\text{off-diag. nnn}) \quad (13)$$

$$E = \frac{B^2}{2g_{\parallel}\beta H} \left\{ I(I+1) - M^2 \right\} \quad (\text{off-diag. hfs}) \quad (14)$$

$$F = \frac{g_{\parallel}^2 \beta^2}{r^3} (1 - 3\cos^2\theta) \quad (\text{diag. nnn}) \quad (15)$$

B. Perpendicular case, $H \perp c$ axis, $g=g_{\perp}$.

If we take our spin Hamiltonian, equation (1), with $H \parallel y$, and re-label the coordinates $x \rightarrow y'$, $y \rightarrow z'$ and $z \rightarrow x'$, it becomes, upon dropping primes,

$$\mathcal{H} = \beta \left\{ g_{\perp} H^z S^z + g_{\parallel} H^x S^x + g_{\perp} H^y S^y \right\} + BS^z I^z + AS^x I^x + BS^y I^y \quad (16)$$

The nearest-neighbor interaction becomes

$$\mathcal{H}_{ij} = K_0 \vec{S}_i \cdot \vec{S}_j + K_1 S_i^x S_j^x \quad (17)$$

We take basis states of the same form as the old, along the new z axis and proceed as before. We now take $H^x = H^y = 0$ in equation (16). To get diagonal terms as in Fig. 3 we replace $g_{\parallel}$ by $g_{\perp}$ and A by B . We find that the diagonal nearest-neighbor term becomes K_0 while the off-diagonal terms become $[K_0 + K_1/2] 2^{-\frac{1}{2}}$. Two more off-diagonal terms appear coupling states

a with f and b with h, but this gives only a small shift since these states differ by the Zeeman energy.

In transforming the dipolar contribution from the next-nearest neighbors, several new terms appear, and angular dependences appear in the mutual spin flip diagonal and $\wedge$ terms. To account approximately for these effects, we average the interaction over the six neighbors and assume coupling to only the totally symmetric mnn state, and proceed as before.

The new "transition matrix" is

$$\begin{vmatrix} -g\beta H - K_0 - 3F' - h\nu & \frac{1}{\sqrt{2}} (K_0 + \frac{K_1}{2}) \\ \frac{1}{\sqrt{2}} (K_0 + \frac{K_1}{2}) & -g\beta H - BM - K_0 + D' + E' - 3F' - h\nu \end{vmatrix} = 0 \quad (18)$$

where now

$$D' = - \left\{ \frac{\beta^2}{4r^3} [g_{\parallel}^2 (1-3\cos^2\theta) + g_{\perp}^2 (1-\frac{3}{2}\sin^2\theta)] \times \sqrt{6} \right\}^2 / BM \quad (19)$$

$$E' = \frac{A^2 + B^2}{4g_{\perp}\beta H} \left\{ I(I+1) - M^2 \right\} \quad (20)$$

and

$$F' = \frac{g_{\perp}^2 \beta^2}{3r^3} (1 - \frac{3}{2}\sin^2\theta) \quad (21)$$

The solutions have the same form as the parallel case.

$$-g\beta H = h\nu + \frac{BM}{2} + K_0 - \frac{E'}{2} - \frac{D'}{2} + 3F' \pm \sqrt{\left(\frac{BM}{2} - \frac{E'}{2} - \frac{D'}{2}\right)^2 + \frac{1}{2} \left(K_0 + \frac{K_1}{2}\right)^2} \quad (22)$$

V. Results and Interpretation

In equations (12) and (22) the $\pm$ signs before the square root must be chosen to give back the state $|e\rangle$ in the limit as the off-diagonal terms $\rightarrow 0$. Thus for $M > 0$, we choose $+$, for $M < 0$ we choose $-$. This has the effect of spreading the hfs spectrum apart symmetrically from the center. The D term has roughly the same effect. The E term leaves the outer lines unaffected, but moves the inner lines up in field, giving an asymmetry. The F term gives only a shift in the whole spectrum.

The most significant effect seen is the deviation of the hyperfine lines from equal spacing, so the overall shift was ignored in the data analysis, and the interactions were determined by the effect of the off-diagonal terms. Since we have measurements in both parallel and perpendicular directions, we can uniquely determine both K_0 and K_1 . Our expressions were fit to the data by varying the g-factor, hyperfine interaction, and the n.n. off-diagonal terms in a least-squares curve fitting computer program. The results could be fit to within our experimental error of about 1 gauss in the parallel direction, and 2 gauss in the perpendicular. Table I shows the result of the computer fit along with the data, and figure 4 shows the experimental spectra.

The parameters of interest, K_0 and K_1 , obtained by the above fitting procedures are shown in Table II, along with results of Baker⁵ and Svare and Seidel⁴. We calculate the dipolar contributions,

$$K_0)_{\text{dipolar}} = \beta^2 g_{\perp}^2 / r^3 \quad (23)$$

$$K_1)_{\text{dipolar}} = - \beta^2 (2g_{\parallel}^2 + g_{\perp}^2) / r^3 \quad (24)$$

using $r = 7.00 \text{ \AA}$ obtained from the x-ray data of Ketelaar, and reducing it by 1% to allow for thermal contraction at helium temperatures, as suggested by Templeton⁶. These values, shown in Table II, are subtracted from the measured values of K_0 and K_1 to obtain the non-dipolar contribution, K_0' and K_1' , shown in Table II. In this table the errors shown for our values of K_0 , K_1 , K_0' and K_1' are obtained by assuming at most a 1% error in the measurement of H due to local field effects in the concentrated NdES. Although for our spherical samples this error should be much smaller than 1%, nevertheless we take 1% to allow for unknown systematic errors. In Table III we give the values of $g_{||}$, $g_{\perp}$, A and B needed to obtain the fit in Table I, along with values obtained by other workers in dilute crystals. The difference between our values and Nd in dilute hosts LaES and YES is not surprising.

Both Baker and Svare and Seidel have used a value for r appropriate to NdES at room temperature, so their calculated dipolar terms are lower than ours by about 3%. This makes a considerable difference in the non-dipolar interaction, and so we have used our calculated dipolar interaction in reducing all sets of data in Table II. We find that our K_0' is not too far from that found by Baker, but that our K_1' is much less than that measured by either Baker or Svare and Seidel.

There has been much theoretical interest recently in the possible mechanism responsible for the non-dipolar interaction^{1,7}. Unfortunately, none of the most probable mechanisms gives an interaction of the correct magnitude, and there are few distinguishing features which would serve to identify the mechanism responsible. Our results have shown that non-dipolar interaction may be smaller than previously thought, and that dilute pair

measurements may give misleading results. This method is now being extended to other ions and other crystal lattices, so perhaps as more data becomes available, it will be possible to identify the interaction.

An important conclusion of our work reported here is that at large values of H/T it is possible to observe sharp EPR lines in magnetically concentrated crystals where the Zeeman term dominates (this is invariably true for paramagnets) and the hfs term is not excessively dominated by pair interactions. In such cases we can make precise measurements of the hfs shifts due to pair interactions and thus determine K_0 and K_1 . When applicable this method is more definitive than resonance experiments on pairs in magnetically dilute crystals.

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Figure Captions

- Fig. 1. Rare-Earth positions in the Ethyl Sulfate lattice: nearest-neighbors (gray) lie along the hexad axis at about $7.07 \text{ \AA}$ while the six next-nearest neighbors (white), lie about $8.8 \text{ \AA}$ away along an axis about 66.4° from the hexad axis.
- Fig. 2. Included in text.
- Fig. 3. Matrix for parallel case.
- Fig. 4. Experimental spectra of the Nd^{143} hfs with the strong $I = 0$ Nd^{142} line in: (a) the parallel direction and (b) the perpendicular direction. Concentration of Nd^{143} is about 1.5% of Nd^{142} . The data are taken at 74.72 GHz and $T = 0.4^\circ \text{K}$.

Table I

(a) Parallel Direction

M	H(exp)	H(calc)	H(exp)-H(calc)
	gauss	gauss	gauss
7/2	15614.8	15615.8	-1.0
5/2	15383.0	15383.0	0.0
3/2	15151.9	15151.3	0.6
1/2	14923.2	14922.9	0.3
-1/2	14685.4	14684.5	0.9
-3/2	14457.2	14457.4	-0.2
-5/2	14229.8	14229.3	0.5
-7/2	14000.8	14001.9	-1.1

(b) Perpendicular Direction

7/2	26891.8	26893.9	-2.1
5/2	26683.8	26684.3	-0.5
3/2	26487.7	26485.3	2.4
1/2	not observed		
-1/2	25989.5	25989.5	0.0
-3/2	25819.4	25816.9	2.5
-5/2	25630.7	25630.5	0.2
-7/2	25440.8	25443.3	-2.5

Table II

In units of 10^{-2} cm^{-1}

	Measured		Non dipolar term	
	K_0	K_1	K_0'	K_1'
This Paper	$0.503 \pm .005$	$-3.57 \pm .03$	$-0.039 \pm .005$	$+0.12 \pm .03$
Baker ⁵	0.49	-3.26	-0.05 ± 0.03	$+0.44 \pm 0.09$
Svare & Seidel ⁴			-0-	+0.39

$$K_0)_{\text{dipolar}} = 0.52$$

$$K_1)_{\text{dipolar}} = -3.696$$

Table III

	$g_{ }$	$g_{\perp}$	A (in cm^{-1})	B (in cm^{-1})
Nd ¹⁴³ :NdES	3.60	2.04	.0388	.0194
	$\pm .04$	$\pm .02$	$\pm .0004$	$\pm .0002$
Nd nn pairs: ⁵				
YES	3.521	2.077		
LaES	3.552	2.062		
	$\pm .001$	$\pm .001$		
Nd single ions ⁵				
Nd: YES	3.547	2.053		
LaES	3.535	2.072	0.038	.020
	$\pm .001$	$\pm .001$

Figure 1

Figure 3

|a> |b> |c> |d> |e> |f> |g> |h>

$$|a> \quad \left(\frac{5g\beta H}{2} + \frac{AM}{2} + K_0 + K_1 \right)$$

$$|b> \quad \left(\frac{3g\beta H}{2} + \frac{AM}{2} \right) \quad \left(\frac{K_0}{\sqrt{2}} \right)$$

$$|c> \quad \left(\frac{3g\beta H}{2} + \frac{AM}{2} \right)$$

$$|d> \quad \left[+ \frac{g\beta H}{2} + \frac{AM}{2} - (K_0 + K_1) \right] \quad \left(\frac{K_0}{\sqrt{2}} \right)$$

$$|e> \quad \left(\frac{K_0}{\sqrt{2}} \right) \quad \left(\frac{3g\beta H}{2} - \frac{AM}{2} \right)$$

$$|f> \quad \left(\frac{K_0}{\sqrt{2}} \right) \quad \left(+ \frac{g\beta H}{2} - \frac{AM}{2} \right)$$

$$|g> \quad \left(+ \frac{g\beta H}{2} - \frac{AM}{2} \right)$$

$$|h> \quad \left(- \frac{g\beta H}{2} - \frac{AM}{2} \right)$$

a)

b)

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