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Nuclear orientation of ^{125}Sb in Pd_2MnSb observed with the Mössbauer effect of ^{125}Te†

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Nuclear orientation of ^{125}Sb in Pd_2MnSb at 139 mK was observed with the Mössbauer effect of ^{125}Te. From the Mössbauer spectrum, the signs of the magnetic moments of ^{125}Sb and $^{125}Te^m$ were found to be positive and negative, respectively. A ^{57}Co Mössbauer thermometer was used to determine the temperature of the sample attached to a ^{3}He-^{4}He refrigerator.

[RADIOACTIVITY oriented ^{125}Sb in Pd_2MnSb; measured Mössbauer effect of ^{125}Te level, $E = 35.5$ keV with ZnTe absorber; ^{125}Sb, $^{125}Te^m$ deduced signs of magnetic moment μ.]

I. INTRODUCTION

Recently unusually large magnetic hyperfine fields have been observed at Sb and Te nuclei in the Heusler alloy Pd_2MnSb by means of Mössbauer measurements on ^{121}Sb and ^{125}Te, respectively.[1,2] These hyperfine fields, $H = +706 \pm 5$ kOe at Sb in Pd_2MnSb and $H = +857 \pm 9$ kOe at Te substituted for Sb in Pd_2MnSb, were determined from the very pure magnetic spectra of the cubic host. The source ^{125}Sb in Pd_2MnSb in which ^{125}Sb decays to ^{125}Te is therefore an excellent host for observing nuclear polarization effects in the magnetically split Mössbauer spectrum of ^{125}Te. In this paper we describe such a nuclear-orientation-Mössbauer-effect (NOME) experiment, from which we were able to derive simultaneously the hitherto unknown signs of the magnetic moments of ^{125}Sb and $^{125}Te^m$.

II. EXPERIMENTAL DETAILS

The source used in this experiment was 3 mC of ^{125}Sb diffused into Pd_2MnSb as described in Ref. 2. This source was fixed with CdBi solder to a copper rod attached to the mixing chamber of a ^{3}He-^{4}He dilution refrigerator. Thermal contact to the ^{3}He-^{4}He phase was established with about 10^4 cm^2 of sintered copper fiber brazed to the copper mixing chamber wall. The single-line ZnTe absorber, containing 8 mg/cm^2 of ^{125}Te, was driven in a sinusoidal velocity mode and maintained at a temperature near 10 K, inside the 4.2 K shield of the refrigerator. The Mössbauer drive system was operated in a vacuum common to the dilution refrigerator.

III. TEMPERATURE DETERMINATION

In order to analyze nuclear polarization effects in a Mössbauer source, the temperature of the source must be accurately known. Radioactive heating very often prevents a source from reaching the temperature of its surroundings.[3,4] A separate experiment was therefore performed to establish the source temperature. A weak ^{57}Co source, diffused into an Fe foil, was attached with CdBi solder on the side of the ^{125}Sb source that was not fixed to the Cu cold finger. A Mössbauer spectrum was recorded (Fig. 1) with a stainless steel absorber. Large asymmetries are observed in this spectrum since the polarization of the ^{57}Co ground state is transferred to the Mössbauer level through the electron capture and gamma ray decay via the 136 keV intermediate level.[5] The spectrum in Fig. 1 corresponds to a temperature of $139\pm^{19}_{15}$ mK that is considerably higher than the mixing-chamber temperature. In this calculation the following parameters were used: H(Co in Fe) = - 289.98 kOe,[6] $\mu(^{57}\text{Co}) = +4.733\ \mu_N$,[7] and the mixing ratio of the 122-keV transition $\delta(E2/M1) = -0.116$.[8] Furthermore, it was assumed that the Fe host produces no depolarization during the decay.[3,4]

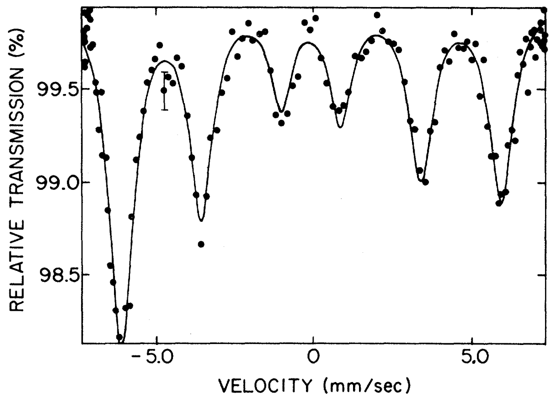

FIG. 1. Mössbauer spectrum of a ^{57}Co in Fe source and a ^{57}Fe in stainless steel absorber, used as a Mössbauer thermometer.

IV. ANALYSIS

Figure 2 shows the spectrum of ^{125}Sb in Pd$_2$MnSb recorded at this temperature. The analysis of the NO effects in this spectrum is somewhat more complicated than for ^{57}Co. As can be seen in the decay scheme[9] given in Fig. 3, the ^{125}Sb parent state decays partly to the 145-keV isomeric state ^{125}Te^{m}. About 26% (obtained by normalizing the gamma intensities in Fig. 3 to 100%) of the feeding of the 35-keV excited Mössbauer level comes from this state, while the remaining feeding of the Mössbauer level comes from the ^{125}Sb ground state via very short-lived intermediate higher excited states of ^{125}Te. As a consequence of this the nuclear polarization effects observed in the ^{125}Te spectrum are due to the NO of both the ^{125}Sb ground state and the ^{125}Te^{m} state, as the latter reorients completely during its long lifetime. The other intermediate states have lifetimes which are much too short for any reorientation effects to be important. However, the nuclear spins and the multipolarities associated with these intermediate beta and gamma transitions influence the amount of polarization transferred to the Mössbauer level ($I^{\pi} = 3/2^{+}$, $E = 35.5$ keV). Several attempts have been made to measure these spins and multipolarities,[9] especially the mixing ratios of the intermediate gamma rays coming from the 671-keV and 463-keV levels, which are mixed E2 + M1 transitions. In our analysis we have used the values measured by Krane *et al.*,[10] since these authors were able to derive both the A_2 and A_4 angular distribution coefficients for these gamma rays directly in their nuclear-orientation-angular-distribution (NOAD) experiment at very low temperature (4-5 mK).

The polarizations of the two parent states are completely determined by the temperature of the source and the values of μH for these two states. The absolute value of the ^{125}Sb ground-state moment $|\mu| = 2.630 \pm 0.035\ \mu_N$ was obtained from a NONMR experiment[11] and the magnitude of the ^{125}Te^{m} isomeric-state moment, $0.93 \pm 0.05\ \mu_N$, from a NOAD experiment,[12] both methods being insensitive to the sign of μH. Although we observe the combined effect of both polarizations, it is in principle possible to derive the sign of both magnetic moments from a single ^{125}Te NOME spectrum. Due to the larger value of μH, the nuclear polarization of the ^{125}Sb ground state will have the largest influence on the asymmetry in the Mössbauer spectrum. Therefore, the sense of the asymmetry gives the sign of μH of the ^{125}Sb ground state. On the other hand, the actual magnitude of the observed asymmetry determines whether the polarized ^{125}Te^{m} state tends to produce an asymmetry in the same or in the opposite direction and thus gives the sign of μH in the ^{125}Te^{m} state.

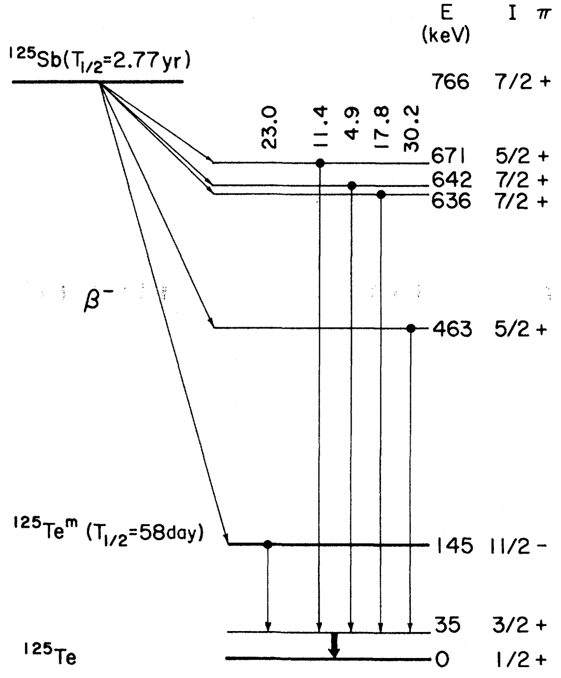

FIG. 3. Part of the ^{125}Sb decay scheme taken from Ref. 9. The relative intensities given (above the 671-keV level) are the number of transitions per 100 decays of the ^{125}Sb ground state.

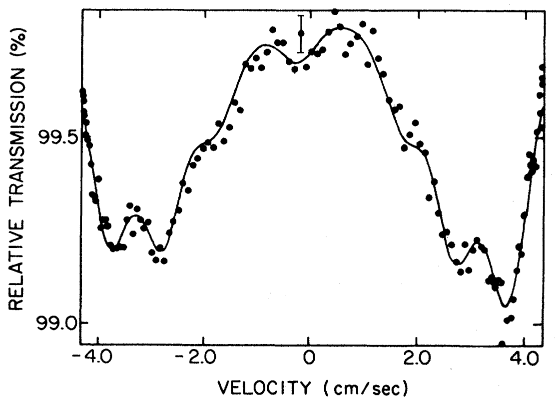

FIG. 2. Mössbauer spectrum of the ^{125}Sb in Pd$_2$MnSb source and a ^{125}Te in ZnTe absorber at 139 mK.

Looking at the two outer lines in the spectrum of Fig. 2, which are the best resolved ones, we notice that the positive velocity line (i.e., the one of smaller energy) has the larger intensity, where we use the convention that positive velocity denotes that the source and absorber have relative motion toward each other. Using the known signs of H and the magnetic moments for the ^{125}Te Mössbauer levels, we infer that this is the $(m_e = +3/2) \rightarrow (m_e = +1/2)$ transition, where the axis of quantization is in the direction of the magnetization relative to which the sign of the internal field is taken. Due to the multipolarities of the intermediate transitions, the feeding from the initial $I_i = 7/2$ ground level of ^{125}Sb to this $m_e = +3/2$ substate is limited to transitions coming from the $m_i = +7/2$ substate and its neighboring substates. From this we conclude that the $m_i = +7/2$ substate must be preferentially populated, and is therefore the lowest substate. This means a positive sign for μH and thus for the magnetic moment of the ^{125}Sb ground state. The same conclusion can be reached by comparing Figs. 1 and 2 and noting that the Mössbauer patterns are essentially mirror images of each other. Since the corresponding Mössbauer states of ^{57}Fe and ^{125}Te have the same signs of μH, we conclude that the ground states of ^{57}Co and ^{125}Sb have opposite signs of μH. This again leads to a positive sign for the moment of ^{125}Sb.

To determine whether the polarization of the ^{125}Te isomeric level is producing an asymmetry in the same direction as the ^{125}Sb ground state, or in the opposite direction, we made an accurate calculation of the asymmetry to be expected in the spectrum of ^{125}Te in Pd$_2$MnSb. Using the populations $P(m_e)$ of the magnetic substates of the excited Mössbauer state, we define a polarization,

$$A = \frac{P(+3/2) - P(-3/2)}{P(+3/2) + P(-3/2)} ,$$

which is also equal to the asymmetry in the intensities of the outermost lines I_+ and I_- at positive and negative velocity, respectively. Thus,

$$A = \frac{I_+ - I_-}{I_+ + I_-} .$$

The calculation of the populations $P(m_e)$ reduces to a properly weighted summation over the populations $P(m_i)$ of all the parent substates multiplied by the transition probabilities $W(m_i \rightarrow m_e)$ between these substates. These transition probabilities involve the product of a beta and a gamma transition and were calculated over all intermediate states. Thus, they involve sums of products of squares of the appropriate Clebsch-Gordan coefficients. As relative populations and relative transition probabilities were used in the calculation, the proper normalization was achieved by imposing the condition that when summed over initial and final substates, the intensity ratios of the intermediate gamma rays as given in Fig. 3, were obtained. The polarizations calculated as a function of temperature are given in Fig. 4, for both a positive and negative magnetic moment of ^{125}Te^m. The observed polarization, shown in the figure, is close to the lower curve and establishes a negative moment for ^{125}Te^m. However, one should look for a reason for the small disagreement. In this connection, we note that the value used for $\mu(^{125}\text{Te}^m)$ was obtained from a NOAD experiment, in which a unique hyperfine field was assumed for all the ^{125}Te^m nuclei implanted in Fe. Recent ME experiments,[13] however, seem to indicate that on implantation in Fe a number of Te ions come to rest at lower field sites. Even after annealing the source at different temperatures, less than 75% of the ions were found to occupy substitutional lattice sites in these experiments. This would indicate that the real $\mu(^{125}\text{Te}^m)$ value is larger than the reported one. The effect would raise the upper curve in Fig. 4 and lower the lower one, thereby improving the agreement with our experiment. It would certainly be worthwhile to remeasure the ^{125}Te^m magnetic moment in a NONMR experiment, where it is possible to observe only the high field site.

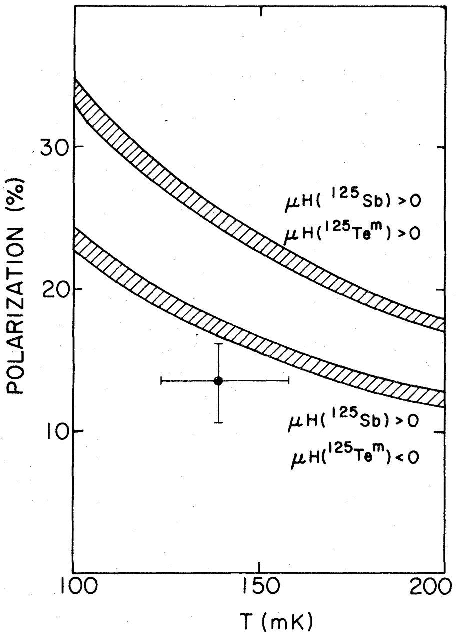

FIG. 4. Calculated and observed polarization in the NOME spectrum of ^{125}Te in Pd$_2$MnSb.

V. DISCUSSION

Using the sign derived from our experiment the ground state moment of ^{125}Sb is $\mu = +2.630 \pm 0.035\ \mu_N$. This value is very similar to the magnetic moment of the $7/2^+$ first excited state of ^{121}Sb, for which we recently obtained $\mu = +2.518 \pm 0.0007\ \mu_N$, and the $7/2^+$ ground state moment of ^{123}Sb, $\mu = +2.5498 \pm 0.0002\ \mu_N$.[14] All of these states are $g_{7/2}$ proton single particle states. Although theoretical calculations by Kisslinger and Sorenson[15] also find very similar values for these moments, their values ($\mu = +3.60\ \mu_N$, $+3.64\ \mu_N$, and $+3.68\ \mu_N$ for ^{121}Sb, ^{123}Sb, and ^{124}Sb, respectively) are much too large. Despite the large deviations, it is interesting to note that the calculations follow the experimentally observed trend ($\mu = +2.518$, $+2.550$ and $+2.630$, respectively). Also for the ^{125}Te^m moment there is a large discrepancy. Again, taking the sign from our measurement, the experimental value becomes $\mu = -0.93 \pm 0.05\ \mu_N$, whereas Kisslinger and Sorensen calculated $\mu = -0.22\ \mu_N$ for this $h_{11/2}$ state in their pairing plus quadrupole model.[15] The same discrepancy with theory exists for all the measured moments of isomeric states in odd Te isotopes, which have been measured in recent years by the NOAD technique.[16] As can be seen in Fig. 5, they all have roughly the same value and based upon our sign determination for ^{125}Te^m, we can expect that they all are negative.

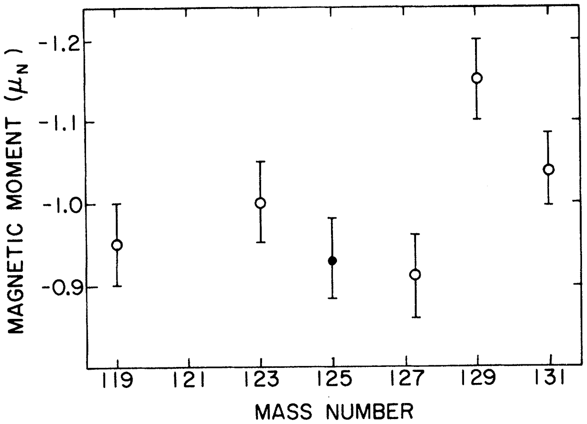

FIG. 5. Magnetic moments of the Te isomeric states. The values are taken from Ref. 16. The signs are not known, except for ^{125}Te^m, where it is taken from this measurement.

The deviations between the calculated and experimental values do not mean that these states cannot be accurately described by the pairing plus quadrupole model. Silverans *et al.*[17] have indicated that for these Te isomeric states, and also for similar states in Sn and Cd isotopes, a much better agreement can be obtained by using a more realistic value for the pairing strength in this calculation.

VI. CONCLUSION

The following conclusions can be drawn from our measurements: (1) the magnetic moment of the ^{125}Sb ground state is positive; (2) the magnetic moment of the ^{125}Te^m isomeric state is negative; (3) there is evidence that the ^{125}Te^m moment may be larger than the value obtained in the NOAD experiment; and (4) source heating is important in many NO experiments, especially those using fairly active sources. A low activity standard source mounted in such a fashion as to be cooled directly only via the source being studied can substantially decrease the uncertainty associated with such experiments by providing an accurate temperature determination.

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