also consistent, if not in precise agreement, with the value calculated from previously determined exchange constants. No interaction effects between the magnons and $\vec{k}=0$ Raman active phonons were seen, although such coupling might be expected. Also, since the crystallographic cell remains the same above and below T_N, no symmetry changes affecting the phonon spectrum were seen. Although not observed in our experiments, it should be possible to see single $\vec{k}=0$, one-magnon Raman scattering. This would take place by a different means from the two-magnon process, probably by spin-orbit interactions as opposed to a pair exchange interaction with the radiation fields. The one-magnon scattering could therefore be much weaker, and its low expected energy, $\sim 6.7\ \mathrm{cm}^{-1}$ from the acoustic branch[16] or $\sim 35\ \mathrm{cm}^{-1}$ from the optic branch, would put it on a large background signal of elastically scattered laser radiation.

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Spin Dependence of the Neutron-Capture Cross Section of Vanadium and the Internal Magnetic Field at Vanadium Nuclei*

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The spin dependence of the neutron-capture cross section of vanadium at 0.115 eV has been measured with the aid of polarized neutrons and polarized vanadium nuclei. It is concluded that the capture cross section of V^{51} is mainly related to spin $J=I-\frac{1}{2}$. In addition, it is shown that the internal field at the vanadium nuclei is less than 4 kOe in very pure vanadium, which apparently does not become ferromagnetic down to 0.06 K.

Transmission experiments with polarized neutrons through a target of polarized vanadium nuclei were carried out at the High Flux Beam Reactor at Brookhaven. Polarized neutrons of 0.115 eV were obtained with the aid of the high-precision crystal spectrometer using (111) reflection from a magnetized 92% Co-8% Fe single crystal.[1] Second-order reflected neutrons were removed from the beam using an erbium filter. Vanadium nuclei were polarized at temperatures between 0.05 and 4.2 K using a magnetic field up to 50 kOe generated with the aid of a superconducting split solenoid. Temperatures below 0.85 K were obtained by adiabatic demagnetization of a chrome-potassium-alum salt assembly thermally connected to the sample. The vanadium sample (10.3 mm thick) and indium (3.35 mm thick) were soldered between two strips of copper, which were connected to the salt assem-

bly by a bundle of thin wires. In addition, an open-beam position was arranged in the sample assembly. The whole insert unit could be moved up and down inside the cryostat and magnet system. In this way we could easily compare the transmissions of the vanadium and indium samples and make corrections for the copper strips. The sample temperature was monitored with a calibrated Speer resistor.[2] The very pure vanadium sample, prepared by repeating electron-beam refinement three times, contained the following main impurities[3]: C (57 ppm), O_2 (112 ppm), Ti (6 ppm), Fe (20 ppm), Ni (12 ppm), Pd (15 ppm), and W (7 ppm).

Several runs were carried out in order to measure the transmission effect ϵ (i.e., the relative difference in transmission for polarized neutrons through polarized targets in the parallel and antiparallel cases[4,5]) of vanadium and indium as a function of temperature and external magnetic field. For small effects, the following formula can be used for analyzing the data:

$$\epsilon = -\tfrac{1}{2}(1+\varphi) f_n^0 N\sigma t \langle\rho\rangle \tfrac{1}{3}[(I+1)/I]\mu H/kT \quad , \quad (1)$$

where f_n^0 is the degree of neutron polarization incident at the sample position when the polarization is parallel to the applied field H, φ is the efficiency of reversing the neutron polarization (usually close to one), N is the number of nuclei per cm^3 of the target (of thickness t), σ is the total cross section for neutrons, I and μ are the nuclear spin and nuclear magnetic moment, and $\langle\rho\rangle$ is a weighted average over the two spin states $I \pm \frac{1}{2}$ open for s-wave neutron reactions. For pure $I+\frac{1}{2}$ or $I-\frac{1}{2}$ reactions ρ is $I/(I+1)$ and -1, respectively. If both reactions are possible, one has to use the weighted average,

$$\langle\rho\rangle = \frac{\sigma_{I+1/2}[I/(I+1)] - \sigma_{I-1/2}}{\sigma_{I+1/2} + \sigma_{I-1/2}} \quad , \quad (1')$$

where $\sigma_{I+1/2}$ and $\sigma_{I-1/2}$ are the cross sections related to the two possible spin states.

From the experimental data, we have determined the slopes of transmission effects versus the inverse of the absolute temperature T. In this way we eliminate possible small effects in the transmission which are independent of temperature, e.g., due to neutron-electron scattering. We have compared the effect of vanadium with indium in order to circumvent the need for accurate measurements of the neutron polarization at the sample position and of the temperatures. In fact, the indium measurements can be considered as a verification of the neutron polarization.

Thus

$$F = \frac{[\Delta\epsilon/\Delta(T^{-1})]_V}{[\Delta\epsilon/\Delta(T^{-1})]_{In}} = \frac{(N\sigma t)_V}{(N\sigma t)_{In}} \frac{Z_V}{Z_{In}} \left(1 + \frac{H_{int}}{H}\right) \quad , \quad (2)$$

where

$$Z = \frac{\sum \sigma_i \rho_i \mu_i [(I_i+1)/I_i]}{\sum \sigma_i}$$

(in units of nuclear magnetons).

We assume that an internal field H_{int} might possibly exist at the vanadium nuclei in the metal. The polarization of indium nuclei is due to the external field only. The factor Z is a weighted average over the various cross-section components (capture and scattering for each spin state and each isotope). The values of $N\sigma t$ can be obtained from the transmission of unpolarized neutrons through unpolarized nuclei applying a small correction for the thin layers of solder and tin used to achieve good thermal contact (the experimental values of $N\sigma t$ agree very well with the values calculated on the basis of known total cross sections). Experimentally, we obtained

$$(N\sigma t)_V/(N\sigma t)_{In} = 0.408 \pm 0.008 \quad .$$

The cross section of indium at 0.115 eV is mainly due to the $(I+\frac{1}{2})$ resonance at 1.456 eV. A small correction is necessary to account for the next resonance at 3.85 eV for which $J = I - \frac{1}{2}$. Hence, we obtained $Z_{In} = 0.98\mu_{In} = 5.40$.

In Fig. 1 the experimental values of F as a function of the inverse of the external field is shown. If we assume that the suggested internal field at the vanadium nuclei is independent of the external field, it is possible to obtain an extrapolated value of F for an infinitely large external field, which has only Z_V as an unknown quantity. From $\lim F = -0.324 \pm 0.045$ as $H \to \infty$, we deduce that $Z_V = -4.31 \pm 0.60$. The error for Z_V is obtained by compounding the other quoted errors quadratically. The total cross section of vanadium at 0.115 eV is

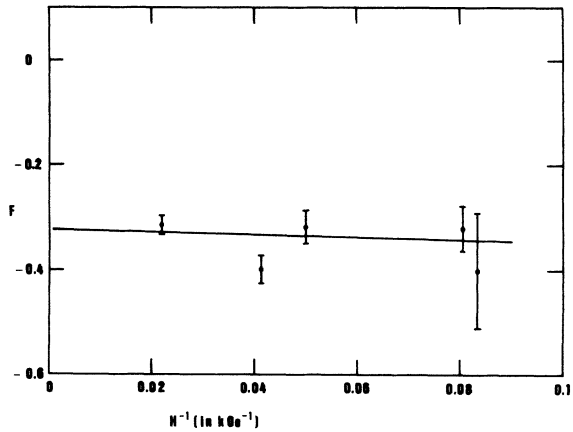

FIG. 1. The ratio of polarized neutron transmission effects for polarized vanadium and polarized indium as a function of the reciprocal magnetic field.

composed of a scattering cross section of 5.10 ± 0.02 b and a capturing cross section of 2.33 ± 0.03 b. The scattering cross section is related to both spin states $I \pm \frac{1}{2}$. From the well-known coherent and incoherent scattering cross sections,[6] the ratio $\sigma_s(I+\frac{1}{2})/\sigma_s(I-\frac{1}{2}) = 0.565 \pm 0.028$ can be derived. The capturing cross section is presumably mainly due to V^{51}, which is 99.76% abundant. However, we assume that a fraction y of the quoted capturing cross section may be due to V^{50} for which only an upper limit of 140 b at thermal neutron energy is known. In addition, the fractions x and x' of $(I+\frac{1}{2})$ capture due to V^{51} and V^{50} are unknown. The calculated expression for Z_V is

$$Z_V = -3.72 + 3.69 \times (1-y) + 0.85y + 2.27x'y \quad . \quad (3)$$

The errors of the numerical factors are sufficiently small to be negligible for our purposes. The first term, which is negative, is related to $(I-\frac{1}{2})$ capture of V^{51}. All other terms, which are due to $(I+\frac{1}{2})$ capture of V^{51} and capture of V^{50}, are positive; hence, any admixture of $(I+\frac{1}{2})$ capture or a contribution to capture due to V^{50} will decrease the computed value of Z_V. Since the measured value of Z_V is within the range of the error equal to the lowest value of Z_V which is possible, we conclude that y, x, and x' are close to zero. Assuming that all the capture is due to V^{51} (thus $y = 0$), it is seen that at most 18% of it is related to the $(I+\frac{1}{2})$ spin state, using two standard deviations as the limit.

From the negligible variation of F with the applied external field, it is concluded that the internal field of the vanadium nuclei is smaller than about 4 kOe.

Formula (1) is only valid of no depolarization of the neutrons occurs during the traverse of the sample as a consequence of magnetic domains. Even in highly magnetized but thick samples, a considerable depolarization occurs if ferromagnetic domains exist. In order to check that this does not happen in the case of pure vanadium, we have measured the polarization of the neutrons with a second magnetized Co-Fe single crystal as a polarization analyzer with the sample assembly either in the open-beam position or with the vanadium in the beam. Two sets of measurements were done, one with the sample at 0.85 K and one with the sample at 0.06 K. In both cases an external field of 22.5 kOe was applied. The change of polarization with the sample in the beam was less than 1% compared to the open-beam polarization measurement. Hence we conclude that pure vanadium does not have ferromagnetic properties even at temperatures as low as 0.06 K.

The apparent "brute-force" polarization of vanadium, which we have observed, is in agreement with measurements of Shull and Ferrier, who studied the electronic and nuclear polarization by slow neutron scattering in a single crystal of vanadium.[7] An internal magnetic field in vanadium has been suggested in another paper[8]; however, this conclusion was based on measurements carried out with considerably less pure vanadium.

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