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MÖSSBAUER EFFECT IN Fe^{57} AT VERY LOW TEMPERATURES

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The recoil-free gamma-ray transition between the 14.4-kev state and the ground state of Fe^{57} has been used to study the hyperfine splittings of these levels in several crystals.[1-4] The studies of the magnetic hyperfine spectra in metallic iron[1] have shown the gamma ray to be split into six components characterized by a ground-state level separation $g_0 = 1.90\times10^{-7}$ ev, and a first excited state splitting of 1.07×10^{-7} ev. The separation of the ground-state levels is equivalent to a temperature of 2.2×10^{-3} °K, which has suggested to us the possibility of observing the effects on the Mössbauer fluorescence pattern that can be produced by cooling a resonant absorber to very low temperatures. In thermal equilibrium the population ratio of the Zeeman levels of the ground state of absorbing Fe^{57} nuclei ($I=1/2$) varies with temperature as $\exp(-g_0/kT)$. Such a population asymmetry would produce an increased absorption coefficient for a transition arising from the $m = -1/2$ Zeeman level relative to transitions in which the m value is reversed in sign. Examination of these absorption coefficients could be made by measuring the transmission of resonant gamma rays from a source at room temperature, by the technique of Doppler-shifting the source relative to the cold absorber.

Larger asymmetries are produced by cooling the source instead of the absorber, since the Co^{57} parent has a magnetic moment about 50 times larger than that of the ground state of Fe^{57}. Success of this scheme depends upon the reasonable expectation that the decay of the Co^{57} through the second and first excited states of Fe^{57} proceeds so rapidly that the Zeeman level populations are unchanged.[5] The process is complicated and the over-all effect reduced, however, by the partial mixing of levels according to the character of the decay. Calculations based upon the assumptions that the electron capture process of Co^{57} is an allowed transition and that the decay from the second to the first excited state of Fe^{57} is either $M1$ or $E2$[6] indicated a partial preservation of the Co^{57} population ratios. These calculations predicted a larger over-all effect than the simpler scheme of cooling an absorber; accordingly the experiment was performed with a cold source and an absorber at room temperature.

A source of approximately 10 millicuries of Co^{57} in natural Fe metal was prepared by the usual technique of plating followed by thermal diffusion,[7] and installed in an adiabatic demagnetization cryostat fitted with thin windows of Mylar plastic and Be metal. The source foil was soldered to the bottom of a capsule containing about 0.1 mole of chromium potassium alum crystals in toluene, and this capsule was thermally attached to a liquid He^3 reservoir by a Pb "heat switch". The 14.4-kev radiation was filtered by a resonant absorber of approximately 2 mg/cm^2 Fe^{57} plated on 0.1 mil nickel foil. The absorber was situated outside the cryostat in a frame which could be oscillated linearly at various speeds by means of a synchronous motor, gear train, and cable system. Transmitted intensities were measured using a 1-mm thick NaI(Tl) crystal and photomultiplier, single-channel pulse-height analyzer, and digital printer. Periods of oscillation were varied from 3 seconds to 5 minutes, and intensities were measured alternately in each direction over the same length of absorber travel. Special care was exercised

in order to avoid transmission of vibration to the absorber and to the source. It proved necessary to conduct the measurements with the pumps stopped and the liquid He^4 at atmospheric pressure.

The Doppler pattern at room temperature showed a central absorption "peak" of 0.6 mm/sec width at half height, corresponding to a "thick" foil having a corrected resonant absorption of approximately 60%. The absorption peaks at ± 2.2 mm/sec Doppler velocity had a comparable width, and a magnitude of 24% relative to the transmission at high velocities; these satellite lines were judged most suitable for the low-temperature study.

The Doppler pattern was also measured with the source at 4°K; the principal change from the spectrum at room temperature was a shift of 0.1 mm/sec toward positive velocities (positive velocity taken as increasing separation between source and absorber), in qualitative agreement with previous investigations.[8,9] The intensity asymmetry between the satellite lines was less than 0.6%, as expected. The satellite lines appeared at -2.1 and +2.3 mm/sec. The character of the Doppler drive system and our expectation that temperatures would change rapidly after demagnetization led us to choose a compromise speed, 2.21 mm/sec, for most of the work at low temperatures. This choice introduced only a 15% loss in sensitivity due to the displacement from the peaks. The chosen velocity was not precisely equally displaced from each line; this led to a basic difference between the intensities at (+) and (-) velocities, giving a ratio $I_-/I_+ = 0.99$. This asymmetry at 4°K formed the baseline for comparison of the peaks at lower temperatures.

The absorber and photomultiplier were removed, a field of 11 kilogauss applied to the salt, and the temperature reduced to 0.5°K by pumping on the liquid He^3 chamber. Thermal equilibrium was obtained in about one hour; the magnetic field was reduced to zero and the magnet moved away, the cryostat pumps were turned off, the liquid He^4 was warmed to its boiling point, and the foil and photomultiplier were replaced. Carbon thermometers attached to the source gave a qualitative measure of the temperature, which was about 0.2°K within 2 minutes after demagnetization. Measurements of the satellite lines were begun at this time; a pronounced intensity asymmetry $I_-/I_+ = 1.03$ was found at the compromise velocity. The ratio increased to about 1.04 during the next two minutes, while the thermometers indicated

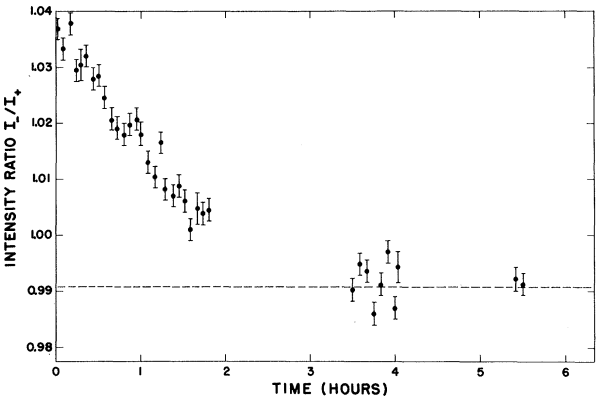

FIG. 1. Ratio of intensities transmitted at ± 2.21 mm/sec during warmup.

continued cooling of the sample. The temperature increased thereafter, reaching a stable value near 1.4°K in six hours, and during this time, the intensity ratio decreased toward 0.99 as shown in Fig. 1. A background correction would increase all ratios by 0.6%. Checks of the intensities at the central absorption peak and at high velocities showed no appreciable changes during the warm-up period.

The observed variation of the absorption pattern with temperature demonstrates that the nuclear spin level population asymmetries are partially preserved through the two nuclear transitions. Uncertainty in the temperature makes inadvisable a quantitative analysis of these data; however, the observed magnitude of the asymmetry as a function of temperature agrees approximately with the preliminary calculation.

It is possible to deduce the direction of the hyperfine magnetic field at Co^{57} nuclei in Fe metal. The ratio I_-/I_+ increases above unity at lower temperatures, implying that the higher energy emission lines are becoming more intense, and the higher energy levels of the first excited state of Fe^{57} are increasingly populated. According to Hanna et al.,[1] this state has an inverted order; i.e., the -3/2 level is highest. Since any decay scheme requires that these levels are preferentially connected to the negative m-value levels of the parent states, the Co^{57} sublevels having negative m values have larger populations. These larger populations must arise from the influence of the Boltzmann factor. Therefore, the lower energy levels have negative m values. One is confident from shell-model considerations that the g value of the Co^{57} nucleus is positive. Since the level scheme is in the same order as that for the ground state of Fe^{57}, which

also has a positive g value, we conclude that the hyperfine field at the Co^{57} nuclei is parallel to that at the Fe. This has been found to be negative with respect to the ferromagnetic domain magnetization[10]; hence the field at the Co^{57} is also opposite to the domain field.

It is amusing to consider that the net maximum asymmetry ratio of 1.05 implies that the sublevels of the 14.4-kev state have populations corresponding to a small negative temperature, approximately -5×10^{-3} °K. The negative spin temperature results from the inversion of the sublevel ordering, and its absolute value is a factor of about 20 lower than the temperature of the lattice and the conduction electrons.

Application of the effect as a low-temperature thermometer appears to be a distinct possibility. We are presently conducting a more quantitative study of the temperature dependence; a detailed report on the work will be submitted.

We wish to thank W. Visscher for several important calculations and helpful discussions.

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SOURCE OF POLARIZED DEUTERONS AND THE VERIFICATION OF ALIGNMENT WITH THE $T(d,n)He^4$ REACTION

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Interest has developed in recent years in the construction of a source of polarized particles, and several suggestions have been made for its accomplishment.[1] A proposal by Galonsky, Willard, and Welton[2] for using the $T(d,n)He^4$ reaction simplifies the detection of the polarized beam. We have constructed an ion source for polarized deuterons and have confirmed the alignment with this reaction.

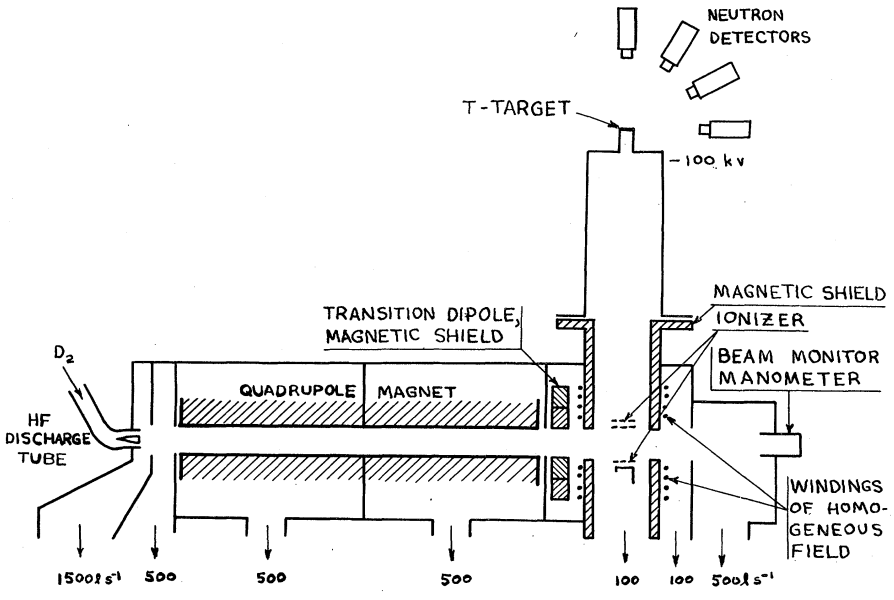

FIG. 1. Schematic diagram of the source.

The course of the particles through the device is shown in Fig. 1. Atoms of deuterium are allowed to diffuse from a high-frequency discharge tube through a region of differential pumping into a strong magnetic quadrupole field. This field is generated by permanent magnets attached to four parallel pole shoes 90 cm long, and has a value of 11 000 gauss at the surface. In this field atoms with strong-field quantum num-