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Compton Profile Due to Magnetic Electrons in Ferromagnetic Iron Measured with Circularly Polarized γ Rays

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The Compton scattering of circularly polarized γ rays was used for studying the linear momentum distribution of electrons with unpaired spins in ferromagnetic iron metal. The observed Compton profile shows a broad minimum around zero momentum. The results are discussed in comparison with those calculated by Wakoh, Kubo, and Yamashita using the augmented-plane-wave method.

The Compton scattering of circularly polarized γ rays can be used for studying the spin density in momentum space in ferromagnetic materials,[1] because the relativistic Compton scattering cross section does depend on the spin of the electron.[2] The present paper reports the first measurement of this type on a ferromagnetic metal.

The Compton scattering cross section for γ rays circularly polarized parallel (antiparallel) to the spin of a single electron at rest is given by[1]

$$(d\sigma/d\Omega)^{\pm}=\tfrac{1}{2}(e^2/mc^2)^2\{(1+\cos^2\theta)[1-(2h\nu/mc^2)(1-\cos\theta)]\pm(2h\nu/mc^2)\cos\theta(\cos\theta-1)\}, \tag{1}$$

where the upper (lower) sign corresponds to the γ-ray polarization parallel (antiparallel) to the electron spin, θ is the scattering angle, and other notations have conventional meanings. The first term in the equation gives the ordinary Compton scattering cross section and the second gives the spin-dependent one. This equation can be easily generalized for many electrons in motion in a magnetic solid and the difference between the cross sections, $(d\sigma/d\Omega)^{+}-(d\sigma/d\Omega)^{-}$, can give information on the magnetic electrons.[1]

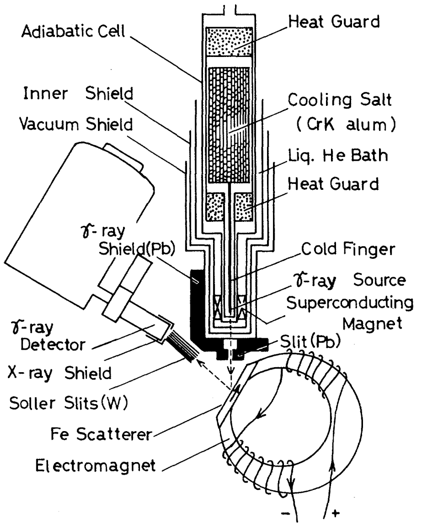

FIG. 1. Apparatus for measuring the Compton profiles by circularly polarized γ rays.

The experimental arrangement is shown in Fig. 1. 10 mCi of ^{57}Co diffused in an iron foil was used as a source. The decay scheme of ^{57}Co is shown in Fig. 2. The source was cooled down to about 40 mK by adiabatic demagnetization of Cr-K alum. The temperature of the source rose to 60 mK in about 4 h. A superconducting magnet

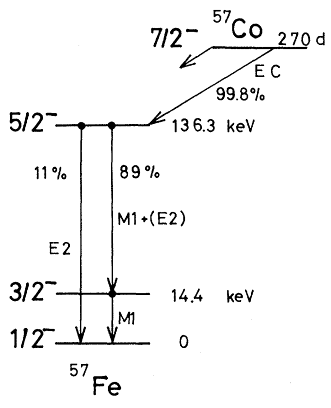

FIG. 2. Decay scheme of ^{57}Co.

served to saturate the magnetization of the iron foil. The direction of magnetization of the iron scatterer was reversed by changing the sign of the exciting current of the electromagnet. γ rays scattered with a scattering angle of 135° were detected by a pure Ge detector, which has resolution of 500 eV at 122 keV. The output of the detector was amplified and fed to a 1024-channel pulse-height analyzer. The divergence of the incident and scattered beams was, respectively, ± 2.5° and ± 2.8° in the plane of scattering.

Figure 3 shows the Mössbauer spectrum of the 14.4-keV γ ray for the source cooled by adiabatic demagnetization and a stainless steel absorber kept at room temperature. The observed asymmetry is brought about by the differences in the population of the Zeeman levels of the ^{57}Co nucleus in the 290-kOe field associated with its iron environment.[3] Disappearence of the absorption peaks 2 and 5 shows that the source was fully magnetized by the superconducting magnet. The peaks 3 and 6 are associated with the right circularly polarized γ rays with $\Delta M = +1$ and the peaks 1 and 4 with the left circularly polarized γ rays with $\Delta M = -1$, where $\Delta M\hbar$ is the angular momentum parallel to the magnetization carried by the γ-ray photons.

The ^{57}Co source emits 14.4- and 122-keV γ rays through magnetic dipole transitions. The latter γ ray was used in the present work because, as seen from Eq. (1), the ratio of the spin-dependent part of the Compton cross section to the normal one is proportional to $h\nu/mc^2$, where $h\nu$ is the γ-ray photon energy and mc^2 is the electron rest mass energy, and is much larger for the 122-keV γ ray than for the 14.4-keV γ ray. Using the decay scheme of ^{57}Co and the source temperature calculated from the Mössbauer spectrum, calculations gave the value of 5.0 as the intensity ratio of the right circularly polarized γ ray to the left one for the 122-keV γ ray emitted parallel to the magnetization of the source.

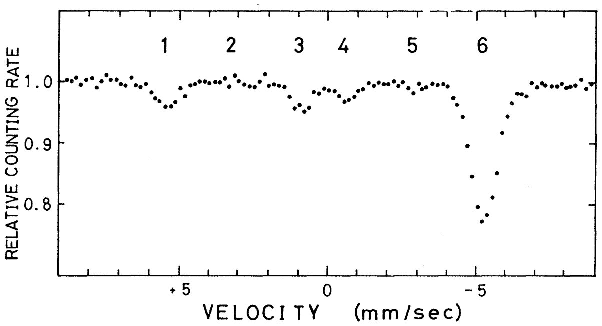

FIG. 3. Source Mössbauer spectrum of the 14.4-keV γ ray obtained at 42 mK.

The Compton profile,[4] $J_+(p_z)$, is proportional to the number of scattered photons when the magnetization of the scatterer is upward, and $J_-(p_z)$ to the corresponding number when the magnetization is downward, with the γ-ray polarization fixed. Here, the variable p_z is the projection of the electron momentum vector on the scattering vector. The Compton profiles $J_\pm$ were accumulated for 139 h during which 40 demagnetization runs were performed. After each demagnetization, J_+, J_-, J_+, J_-, J_+, and J_- were successively accumulated for 400, 800, 400, 400, 800, and 400, sec and this set of measurements was repeated until the source temperature reached about 60 mK. The temperature was monitored by means of the Mössbauer thermometry using the 14.4-keV γ ray in the early stage of the work and later by means of the nuclear orientation thermometry using the 136-keV γ ray emitted from the source (see Fig. 2).

Figure 4 shows the difference between the Compton profiles, $\Delta J(p_z) = J_+(p_z) - J_-(p_z)$. To increase statistical accuracy, the data for plus and minus p_z were averaged. The resolution of the spectrometer in the momentum space, including effects of both energy and angular resolutions mentioned before, was $\Delta p_z = 0.85$ a.u. Since the difference ΔJ is small by two orders of magnitude compared with the J_+ or J_- itself and a long duration is required for the accumulation of data, severe stability of the amplifier and analyzer had to be ensured. A digital spectrum stabilizer was

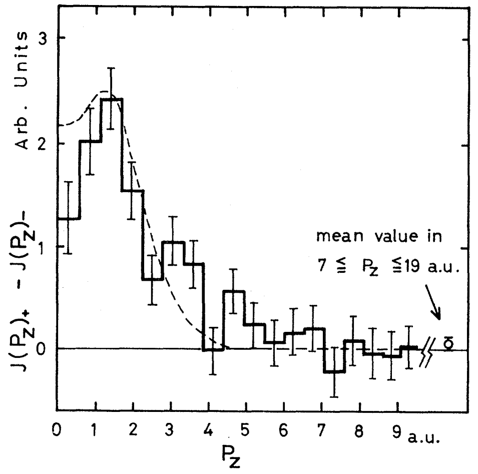

FIG. 4. Measured Compton profile, $J_+ - J_-$. The broken line is the profile calculated by Wakoh, Kubo, and Yamashita.

successfully used to control both the gain and zero drifts of the spectrometer within 0.03% of the half-width of the Compton profile. Errors due to the instability of the spectrometer could then be estimated to be at most 3% in the observed ΔJ. Corrections for our experimental geometry with the finite collimation of the incident and scattered beams, efficiency of the pure Ge detector, effect of the low-energy tail in the spectrometer described by Eisenberger and Reed,[4] absorption and multiple scattering of the γ rays in the scatterer, and Compton cross section are estimated to give at most 10% change in the shape of $\Delta J(p_z)$, and these corrections were already made in our experimental Compton profile in Fig. 4. The mean value ΔJ observed in the high-momentum region $7 \leqslant p_z \leqslant 19$ a.u. is shown in the right of Fig. 4. Its statistical error is also shown in the figure. The value for ΔJ in this high-momentum retion is due to the inner-shell electrons which have no net spins and the value should be zero, with which the observed value agrees well. The result suggests that systematic errors do not play any important role in the observed ΔJ. Errors indicated in Fig. 4 are the statistical ones.

A broad minimum around zero momentum indicates that the magnetization for some of the electrons with low momenta is opposite to that for majority electrons with positive magnetization. A similar feature was found in experiments on annihilation of polarized positrons[5] and on diffraction of polarized neutrons.[6] Compared with these, the results obtained from polarized γ rays are believed to provide the most straightforward and direct comparison with those of band structural calculations. From the results shown in Fig. 4, the negative spin polarization is estimated to be $0.3_2\mu_{\mathrm{B}}$. This is a little larger than the value $0.21\mu_{\mathrm{B}}$ obtained by the neutron diffraction experiment.[6]

The theoretical profile ΔJ has recently been calculated from the spin-dependent wave functions by Wakoh, Kubo, and Yamashita using the augmented-plane-wave method.[7] The broken line in the figure is the calculated one. To make a comparison with the observed profile, the calculated profile is modified taking account of the instrumental broadening and is normalized to the experimental Compton profile area. Although both the profiles have a characteristic volcano structure with a minimum around $p_z = 0$, quantitative discrepancies are found in both the low- and high-momentum regions ($p_z < 1$ and $p_z > 3$ a.u.). According to the calculation, the major part of the Compton profile $\Delta J(p_z)$ is attributed to the d-like components of the conduction electrons which have a flat distribution in the low-momentum region ($p_z < 1$ a.u.), while the minimum of the profile is attributed to the s-p-like components. The depth of the minimum may give the measure of their negative spin polarization and the degree of the s-d exchange interaction. Therefore, the discrepancies show that the calculation should be modified to give more s-p components with negatively polarized spins in the low-momentum region ($p_z < 1$ a.u.) and more d components with positively polarized spins in the high-momentum region ($p_z > 3$ a.u.). The discrepancy in the high-momentum region might partly be attributed to many-body effects.

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