MAGNETIZATION AND MÖSSBAUER EFFECT STUDIES OF RFe₆Al₆

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Binary intermetallic compounds RFe₁₂ (R = rare-earth metal) with tetragonal crystal structure of the ThMn₁₂ type do not exist nevertheless the structure can be stabilized by a third element M. The Fe content x in the RFe₆M₁₂₋ₓ quasibinary compounds may vary from 3.5 (RFe₃.₅Al₈.₅) to 11 (RFe₁₁Ti). At x ~ 4, the Fe magnetic moments are in the basal plane and order antiferromagnetically. At high x values, the compounds are uniaxial ferromagnets. At intermediate Fe content, these competitive exchange and anisotropic interactions lead to complicated non-collinear magnetic structures [1].

In the present work we investigated two representatives of such systems, LuFe₆Al₆ and HoFe₆Al₆, by the magnetization measurements on the single crystals (grown in tri-arc furnace by Czochralski method) and the Mössbauer effect study. LuFe₆Al₆ is a ferromagnet with spontaneous moment $M_s = 10 \mu_B$ and Curie temperature $T_C = 325$ K. The magnetic anisotropy is of the easy-plane type with anisotropy field of 3 T and negligible anisotropy within the easy plane. HoFe₆Al₆ is a ferrimagnet with exact compensation of the Ho and Fe sublattices at low temperatures, $M_s = 0$. At elevated temperatures, $M_s$ passes through a wide maximum (4.2 $\mu_B$ at 200 K) and vanishes at $T_C = 315$ K (Fig. 1). As in LuFe₆Al₆, the magnetic anisotropy is of the easy-plane type. However, there is a noticeable anisotropy within the easy plane with the [110] easy-magnetization axis.

Mössbauer spectra of LuFe₆Al₆ could be fitted with three different hyperfine sites of iron – all of them having simultaneously the electric quadrupole interaction of the axial character. A magnetic field is co-axial with the principal axis of the electric field gradient (EFG) for the site with the highest field (18.2 T at 4.2 K). It makes an angle of about 45° with the EFG axis for the intermediate field (16.2 T at 4.2 K) and it is perpendicular to the EFG axis for the site with the smallest field (9.7 T at 4.2 K). Quadrupole coupling constants are positive except for the site with the smallest field, where the negative coupling constant shows significant increase in the absolute terms versus lowering temperature.

HoFe₆Al₆ spectra can be fitted with four sites, and the additional site comes from splitting of the previous site with the intermediate hyperfine field. The site with maximum field (17.2 T at 4.2 K) exhibits some finite angle between field and EFG axis changing from above the magic angle to below the magic angle, while lowering temperature, i.e., between 160 K and 80 K.

The number of different hyperfine sites of iron could vary in the compounds RFe₆Al₆ from two to four depending on the type of magnetic order [2].

![Fig. 1](image1.png)

**Fig. 1** Temperature dependencies of $M_s$ obtained from the magnetization curves along the [110] axis for HoFe₆Al₆ and LuFe₆Al₆. The dashed line represents the magnetization of the Ho sublattice $M_{Ho}$.

![Fig. 2](image2.png)

**Fig. 2** Mössbauer spectra for powdered samples of LuFe₆Al₆ and HoFe₆Al₆ vs. temperature.

Iron-based superconductors investigated by Mössbauer spectroscopy

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A review on the recent developments on the investigation of the iron-based superconductors by the Mössbauer spectroscopy is to be given with the particular attention paid to the “11”, “111”, “122” and “1111” compounds. $^{57}$Fe Mössbauer spectroscopy is crucial here, as iron is the main component of these compounds responsible for the superconductivity. On the other hand, 14.41-keV transition in $^{57}$Fe is very sensitive to the local magnetic order. Hence, one can investigate interplay between magnetic order of the 3d band and Cooper pair formation leading to the superconducting state. In particular, even very small electronic magnetic moment on iron atoms could be detected at low temperature applying strong external magnetic field. Therefore Mössbauer spectroscopy could be used to find eventual co-existence of the 3d magnetic order and superconductivity within the same phase. Such co-existence would require exotic coupling mechanisms for the Cooper pair formation like coupling via para-magnons leading to the non-zero spin Cooper pairs and subsequently to the Ferrel-Fulde-Larkin-Övchinnikov (FFLO) phase. For standard phonon coupling leading to the $S=0$ Cooper electron/hole-based pairs co-existence is virtually impossible due to the strong scattering of the electron spins by the polarized band. On the other hand, for many compounds being superconductors it was found that iron has null magnetic moment e.g. for FeSe [1], LiFeP [2], LaFeAsO$_{1-x}$F$_x$ [3] and La$_{1-x}$Ca$_x$FePO [4]. $^{151}$Eu Mössbauer spectroscopy could be used for some “122” compounds containing Eu as one of the major components. Eu$^{3+}$ ions have large electronic magnetic moment without orbital contribution localized in the deep 4f band. Hence, one can expect either freezing of the above moments into spin-glass or even long range magnetic order (including ferromagnetism) co-existing with the superconducting state within the same volume. Such order is easy to detect via the hyperfine field on the europium nucleus. Magnetic order in the precursors of the “122” superconductors could be studied in details by the $^{52}$Fe Mössbauer spectroscopy. The most important question is concerned with the presence of de-localized electronic magnetic moment in the form of the spin density waves (SDW). Mössbauer spectra are particularly sensitive to the incommensurate SDW.