Magnetic Properties of Mixed Cobalt-Aluminum Ferrite Nanoparticles

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The magnetic properties of nanocrystalline CoFe2−xAlxO4 (0 ≤ x ≤ 1) spinel ferrites have been investigated by means of Mössbauer spectroscopy, using a vibrating sample magnetometer (VSM). The crystal structure was found using an X-ray diffractometer (XRD) and verified using transmission electron microscopy (TEM). Substitution of Al content x in cobalt ferrite caused a decrease in particle size, lattice parameter, and Curie temperature. The Mössbauer and VSM studies for these nanoparticles revealed the existence of a non-collinear spin arrangement at the surface of the CoFe2−xAlxO4 nanoparticle. The saturation magnetization changes with increasing Al content due to the effect of cation distribution in tetrahedral and octahedral sites and due to a change in ferrimagnetic structure. The particle size effects on the coercivity at 290 K were studied. The phase change in the Mössbauer from ferrimagnetic to paramagnetic with nanoparticles is due to the fact that the particles are too small to maintain the ferrimagnetic parameters.

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I. INTRODUCTION

Magnetic properties of nanoparticles find wide technological applications, such as high density recording, magnetic refrigeration, ferrofluids, spintronics, drug delivery, etc. [1, 2]. One of the most unique and striking aspects of the behavior of nanoparticles is superparamagnetism. Properties like the blocking temperature and coercivity can be controlled by varying the particle size and chemical composition. Therefore intensive investigations have been carried out to improve the magnetic properties of such nanoparticles. Efforts have increased recently for the synthesis and characterization of CoFe2O4 materials because of high coercive force field, mechanical hardness, and chemical stability, which are important for magnetic recording, magneto-optical recording, and electronic devices [3]. For nanoparticles having large surface/volume ratio, the spin disorder may modify the magnetic properties [4, 5]. Spin-disorder may occur because of broken exchange bonds that produce a spin glass like surface, lowering the coordination of the surface atoms with a high anisotropy surface layer [4, 5]. Disorder is a strong effect in nanocrystalline ferrites where the super-exchange interaction occurs through the oxygen ions. The cation distribution may also differ at surface and non-surface atoms [4, 6, 7].

Cobalt ferrite is a partially inverse spinel with formula (CoFe1−x) [Co1−x Fe1+x] O4, where the round and square brackets represents tetrahedral (A) and octahedral [B] sites, respectively [4, 9, 10]. The presence of large magnetocrystalline anisotropy with reasonable
magnetization values makes cobalt ferrite a promising hard magnetic material, provided it can be obtained in a stable single domain particle size [11]. However, for nanosized cobalt ferrite the room temperature coercivity values are reported to be 500–2000 Oe, far below the theoretically estimated one [11].

Several researchers have reported on Cd, Cr, Mn, Ti, Zn, Gd, Pr, and Nd substituted cobalt ferrite [2, 12–17]. To our knowledge, there are very few detailed studies on aluminum substituted cobalt ferrite synthesized by the sol-gel method. In the present work, we report the sol-gel synthesis, structural, and magnetic properties of Al doped cobalt spinel ferrite nanoparticles. The primary goal of this paper is to gain insight into the relationship between the change of magnetic properties with the change of particle size and chemical composition. Very few details are available concerning the effect on magnetic properties of Al doped cobalt ferrite nanoparticles. Therefore a systematic study has been carried by varying the Al content to see the significant effect on the magnetic properties of cobalt ferrite nanoparticles.

II. EXPERIMENTAL PROCEDURE

Nanocrystalline powders of CoFe$_{2-x}$Al$_x$O$_4$ (0 < $x$ < 1) were prepared by the sol-gel auto-ignition method. AR grade citric acid (C$_6$H$_8$O$_7$H$_2$O), cobalt nitrate (Co(NO$_3$)$_2$.6H$_2$O), ferric nitrate (Fe(NO$_3$)$_3$.9H$_2$O), and aluminum nitrate (Al(NO$_3$)$_3$.9H$_2$O) (>= 99%) were used as starting materials. The molar ratio of metal nitrates to citric acid was taken as 1:3. The preparation technique has been presented elsewhere [18]. The obtained ferrite powders were calcined at 500°C for four hours to get the final product. The formation of the cubic spinel structure of cobalt ferrite is confirmed by Inel X-ray diffraction analysis. The average particle size $D$ was determined from line broadening (311) reflection using the Scherrer formula [19],

$$D = \frac{0.9\lambda}{\beta \cos \theta},$$

where $\beta$ is the angular line width at half maximum intensity and $\theta$ the Bragg angle for the actual peak.

The transmission electron microscopy (TEM) measurements for the $x = 0.0$, 0.4, 1.0 samples were carried using a Philips CM-12 transmission electron microscope. The ac susceptibility measurements for the samples were carried out using a double-coil set-up [20] operating at a frequency of 263 Hz and in the RMS field of 39.8 Am$^{-1}$. Magnetic measurements at 290 K were carried using a PARC EG&G vibrating sample magnetometer VSM 4500, at room temperature with maximal applied magnetic fields up to 0.95 T. The Mössbauer spectra were obtained at 300 K in the transmission geometry with a source of 25 mCi $^{57}$Co(Rh).
III. RESULTS AND DISCUSSION

Nanometer size CoFe$_{2-x}$Al$_x$O$_4$ particles in the size range 39 nm to 6 nm were prepared by the sol-gel method. Figure 1 shows the X-ray diffractograms of the CoFe$_{2-x}$Al$_x$O$_4$ (0 ≤ x ≤ 1) nanoparticles, and the XRD patterns clearly indicate that the prepared samples contain a cubic spinel structure [21]. As the Al content $x$ increased the diffraction peaks became broader, that may be due to the presence of a nanocrystalline structure, and the broadening with $x$ points to the decrease of characteristic size. The results are as shown in Table I. A similar trend was reported in the previously published work on the NiFe$_{2-x}$Al$_x$O$_4$ system, [18] and [22].

The values for the lattice constants were obtained for all the samples using XRD data with an accuracy of ±0.002 Å. The values of the lattice constants are listed in Table I. It is observed from Table I that the lattice constant decreases with increasing aluminum content $x$. This behavior of the lattice constant with aluminum content $x$ is explained on the basis of the difference in the ionic radii of Fe$^{3+}$ and Al$^{3+}$. In the present series CoFe$_{2-x}$Al$_x$O$_4$,  

### TABLE I: Particle size $D$ from XRD and TEM, Lattice constant $a$, saturation magnetization $M_s$, coercive field $H_c$, remanent magnetization $M_r$, and curie temperature $T_C$.

<table>
<thead>
<tr>
<th>Sample $x$</th>
<th>$D_{XRD}$ (nm)</th>
<th>$D_{TEM}$ (nm)</th>
<th>Lattice parameter $a$ Å</th>
<th>$M_s$ (emu.g$^{-1}$)</th>
<th>$H_c$ [Oe]</th>
<th>$M_r$ (emu.g$^{-1}$)</th>
<th>$T_C$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>39</td>
<td>36</td>
<td>8.335</td>
<td>63.7</td>
<td>1362</td>
<td>28.5</td>
<td>799</td>
</tr>
<tr>
<td>0.2</td>
<td>37</td>
<td>32</td>
<td>8.334</td>
<td>60</td>
<td>1305</td>
<td>26.9</td>
<td>760</td>
</tr>
<tr>
<td>0.4</td>
<td>28</td>
<td>28</td>
<td>8.321</td>
<td>47.2</td>
<td>1191</td>
<td>21.1</td>
<td>693</td>
</tr>
<tr>
<td>0.6</td>
<td>24</td>
<td>21</td>
<td>8.302</td>
<td>39.3</td>
<td>1108</td>
<td>17.4</td>
<td>628</td>
</tr>
<tr>
<td>0.8</td>
<td>8</td>
<td>8</td>
<td>8.202</td>
<td>29</td>
<td>868</td>
<td>12.4</td>
<td>585</td>
</tr>
<tr>
<td>1.0</td>
<td>6</td>
<td>7</td>
<td>8.184</td>
<td>17.6</td>
<td>856</td>
<td>5.47</td>
<td>512</td>
</tr>
</tbody>
</table>
larger Fe$^{3+}$ (0.67 Å) ions are replaced by smaller Al$^{3+}$ (0.51 Å) ions; therefore, a decrease in the lattice constant takes place. A similar trend was found in Cu-Cd ferrite with aluminum substitution [23].

Figures 2 (a), (b), (c), and (d) present typical TEM photographs for the samples with $x = 0.0$, 0.4, 0.8, and 1.0. The particle size evaluated from the TEM photographs is provided in Table I. As seen from Table I, the particle size measured from XRD and TEM are in good agreement with each other.

The Curie temperature ($T_C$) obtained from the a.c. susceptibility data are shown in Figure 3 with increasing $x$ and also are listed in Table I. It is evident from Figure 3 that $T_C$ decreases almost linearly with increasing $x$ up to $x = 1.0$, suggesting a change in magnetic
ordering because of the nano-particulated structure.

The magnetization of CoFe$_{2-x}$Al$_x$O$_4$ (0 $\leq$ $x$ $\leq$ 1) nanoparticles has been investigated by a hysteresis curve measurement at 290 K, as shown in Figure 4. The corresponding parameters obtained are listed in Table I. Cobalt ferrite is a well-known hard magnetic material, and it needs a high magnetic field to saturate. On the other hand, the saturation magnetization values were affected by increasing the Al content as a consequence of decreasing crystallinity and particle size, and also a composition which effects the spin per formula unit. A similar behavior has been reported for CoFe$_2$O$_4$ prepared by the polymerized complex method [22]. As seen from Figure 4, the loops could not be saturated with the available maximum field of 0.95 T. This indicates the presence of superparamagnetic and single domain particles with large anisotropy in the material [24]. The magnetization decreases with decreasing particle size. $M_{\text{sat}}$ is determined by fitting the high field reversible part (above 0.7 T) of the measured $M(H)$ data by the well known Langevin dependence

$$M(H) = M_{\text{sat}} \left(1 - \frac{k_B T}{M_{\text{sat}} \rho V_{\text{eff}} \mu_0 H}\right)$$

where $T$ is the temperature, $\rho$ is the density of material, $V_{\text{eff}}$ the effective value of the particles' volume, and the other symbols have the usual meaning.

It is seen that saturation magnetization $M_S$, remanent magnetization $M_R$ and coercive field $H_C$ decrease with decreasing particle size (Figure 4) and with the increasing fraction of superparamagnetic particles. The saturation magnetization of ferrimagnetic or ferromagnetic materials usually decreases with decreasing particle size, due to the existence of spin canting in small magnetic particles [24]. Spin canting may be due to the factors such as the surface effect [4, 24] and the finite size effect [24–26]. The reduction of magnetization values may have been caused by non-collinearity of the magnetic moments at the surface of the nanoparticles, resulting in a decrease in the magnetization for high Al content [4, 27]. The same argument is valid for remanent magnetization also, and the same phenomenon is explained in one of our papers on NiFe$_{2-x}$Al$_x$O$_4$ [18]. The variation of coercivity with
TABLE II: $\eta_B$ calculated from VSM, Theoretical Neel’s model and Mossbauer.

<table>
<thead>
<tr>
<th>Sample $x$</th>
<th>$\eta_B$ from VSM</th>
<th>$\eta_B$ from Neel’s model</th>
<th>$\eta_B$ from Mossbauer</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>2.67</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>0.2</td>
<td>2.45</td>
<td>2.38</td>
<td>2.786</td>
</tr>
<tr>
<td>0.4</td>
<td>1.88</td>
<td>1.76</td>
<td>2.084</td>
</tr>
<tr>
<td>0.6</td>
<td>1.52</td>
<td>1.3</td>
<td>1.67</td>
</tr>
<tr>
<td>0.8</td>
<td>1.09</td>
<td>1.14</td>
<td>1.393</td>
</tr>
<tr>
<td>1.0</td>
<td>0.64</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The particle size is explained on the basis of the domain size diameter of the particle and crystal anisotropy [27, 28]. Also, it may be caused by lowering the anisotropy barrier in small particles and the small anisotropy density in the case of higher Al content [29]. As the net magnetic moment in the ferrimagnetic ferrite material depends on the magnetic ions occupying the tetrahedral and octahedral sites, the reduction of magnetization as a function of non-magnetic Al ions is clear.

![Variation of $\eta_B$ with Al concentration at 300 K obtained from magnetization, theoretical prediction of Néel and Mössbauer data.](image)

The $^{57}$Fe Mössbauer spectra were recorded at 300 K for the samples CoFe$_{2-x}$Al$_x$O$_4$ (0 ≤ $x$ ≤ 1) nanoparticles. Since cobalt aluminate is a partially inverted spinel, Al$^{3+}$ can occupy both A (tetrahedral) and B (octahedral) sites. The cation distribution has been derived from X-ray diffraction, magnetization, and Mössbauer results. Co$^{2+}$ and Al$^{3+}$ ions migrate at A sites at the beginning of substitution in the ratio 7:1 (Co:Al) and the Fe$^{3+}$ concentration of A and B site decreases simultaneously with increasing $x$ in the ratio of 2:3 up to $x$ = 0.4. Thereafter the Fe$^{3+}$ concentration of A and B sites decreases with increasing Al content $x$ in the ratio 9:11 for $x$ = 0.6 to 1. The cation distribution obtained for CoFe$_{2-x}$Al$_x$O$_4$ are represented as
\( (i) \ x = 0.0 \text{ to } 0.4 \)

\[
(\text{Fe}_{1-x}^{3+}\text{Co}_{x}^{2+}\text{Al}_{0.05x}^{3+})^A [\text{Co}_{1-0.35x}^{2+}\text{Al}_{0.95x}^{3+}\text{Fe}_{1-0.6x}^{3+}]^B \tag{3}
\]

\( (ii) \ x = 0.4 + y, \ y = 0.0 \text{ to } 0.6 \)

\[
(\text{Fe}_{0.84-0.45y}^{3+}\text{Co}_{0.14+0.3y}^{2+}\text{Al}_{0.02+0.15y}^{3+})^A [\text{Co}_{0.86-0.3y}^{2+}\text{Al}_{0.38+0.85y}^{3+}\text{Fe}_{0.76-0.55y}^{3+}]^B \tag{4}
\]

According to Néel’s two sublattice model of ferrimagnetism [30], the Néel magnetic moment per formula unit \( \mu_B, \eta^N_B \) is expressed as

\[
\eta^N_B = M_B(x) - M_A(x) \tag{5}
\]

Where \( M_B \) and \( M_A \) are the B and A site magnetic moments in \( \mu_B \). The calculated \( \eta^N_B \) values for \( x = 0.0 \) to 1 using equations (3) and (4) are shown in Table II and in Figure 5 as a solid line. The calculated \( \eta^N_B (\mu_B) \) values for \( x = 0.0 \) to 0.8 nearly agree with the experimentally found values, confirming the collinear spin ordering.

\[\text{FIG. 5: Mössbauer spectra of CoFe}_{2-x}\text{Al}_x\text{O}_4 (x = 0.0–1.0).}\]

Mössbauer spectra recorded at 300 K for the \( x = 0.0 \) to 1.0 samples are displayed in Figure 6. In Figure 6, the spectra (\( x \leq 0.4 \)) exhibit normal Zeeman split sextets, one
TABLE III: Sites (tetrahedral ‘A’ and octahedral ‘B’), isomer shift (mm/s), quadrupole splitting (mm/s), hyperfine field (KOe), central quadrupole splitting (mm/s).

<table>
<thead>
<tr>
<th>Sample x</th>
<th>Site</th>
<th>IS(mm/s)</th>
<th>QS(mm/s)</th>
<th>Hf (KOe)</th>
<th>Central QS (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>B</td>
<td>0.50 ± 0.02</td>
<td>0.07 ± 0.04</td>
<td>503 ± 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.17 ± 0.02</td>
<td>-0.13 ± 0.04</td>
<td>499 ± 1</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>B</td>
<td>0.30 ± 0.02</td>
<td>0.05 ± 0.04</td>
<td>510 ± 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.43 ± 0.02</td>
<td>-0.03 ± 0.04</td>
<td>477 ± 1</td>
<td></td>
</tr>
<tr>
<td>0.4</td>
<td>B</td>
<td>0.27 ± 0.03</td>
<td>0.00 ± 0.04</td>
<td>504 ± 1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.38 ± 0.03</td>
<td>-0.05 ± 0.04</td>
<td>474 ± 2</td>
<td></td>
</tr>
<tr>
<td>0.6</td>
<td>B</td>
<td>0.30 ± 0.03</td>
<td>0.02 ± 0.04</td>
<td>497 ± 7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.32 ± 0.03</td>
<td>0.00 ± 0.03</td>
<td>467 ± 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.40 ± 0.03</td>
<td>-</td>
<td>1.11 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td>B</td>
<td>0.28 ± 0.03</td>
<td>0.02 ± 0.04</td>
<td>488 ± 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>0.32 ± 0.03</td>
<td>0.02 ± 0.04</td>
<td>444 ± 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.32 ± 0.02</td>
<td>-</td>
<td>0.85 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>B/A</td>
<td>0.29 ± 0.03</td>
<td>0.00 ± 0.05</td>
<td>476 ± 2</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.31 ± 0.03</td>
<td>-</td>
<td>0.84 ± 0.08</td>
<td></td>
</tr>
</tbody>
</table>

FIG. 7: Variation of hyperfine fields ($H_f$) with chemical composition $x$.

due to the Fe$^{3+}$ ions at the tetrahedral (A) site and the other due to Fe$^{3+}$ ions at the octahedral [B] sites, and for $x = 0.6$ to 1.0 the spectra display the co-existence of magnetic as well as paramagnetic components, which indicate ferrimagnetic behavior of the samples in conformity with the magnetization data for $x = 0.0$ to 1.0. The solid lines through the data points in Figure 6 are the results of the computer fits of spectra obtained assuming two magnetic sextets for $x \leq 0.4$ and $0.6 \leq x \leq 1.0$ and assuming two magnetic sextets and a central paramagnetic doublet. The intensity of the central doublet increases with respect to the magnetic sextets on increasing $x$ from $x = 0.6$ to 1.0. The parameters derived from the least square fits are listed in Table III. The experimental integrated intensity ratios of
A and B sites Fe$^{57}$ spectra and those calculated on the basis of cation distribution given in equations (3) and (4) are in close agreement with each other. This confirms the cation distribution formula (Equations (3) and (4)) given above, as it agrees with the Mössbauer and magnetization data satisfactorily. Figure 7 shows the variation of the hyperfine fields. It is evident from Figure 7 that the hyperfine fields ($H_A$ and $H_B$) decrease with increasing non-magnetic Al content $x$, demonstrating reduction in ferrimagnetic behavior and magnetic coupling, $J_{AB}$, with increasing $x$ values, in agreement with the magnetization results.

The isomershifts (IS (A) and IS (B) Table III) showing very little change in the S-electron distribution of Fe$^{3+}$ is partially influenced by Al substitution. The random behavior of the observed quadrupole splitting of the A and B sites for $x = 0.0$ to 0.8 is due to the random distribution of Co and Al ions around iron ions. The appearance of the paramagnetic doublet superimposed on a six line pattern (Figure 6) for $x = 0.6$ to 1.0 indicates the presence of short range magnetic ordering (superparamagnetic clustering) induced by the fine particle size effects. Thus as the non-magnetic Al content $x$ increases in CoFe$_{2-x}$Al$_x$O$_4$ the magnetic coupling (ferrimagnetism) is weakened from that of cobalt ferrite $x = 0.0$ to that of $x = 1.0$. It is interesting to note from Figure 6 that the Mössbauer spectra for $x = 0.6$ to 1.0 show in addition to hyperfine fields an additional quadrupole doublet corresponding to paramagnetic behavior. The intensity of this quadrupole doublet increases with increasing Al concentration from $x = 0.6$ to 1.0, and also its quadrupole splitting decreases with increasing non-magnetic Al content $x$, which is evident from Figure 6. This unusual behavior may be attributed to the nano-particle size effect.

An indirect check for the presence of canted spin (non-collinear) structure follows from the apparent proportionality between $|H_n|$ and the average sublattice magnetization. It can be shown that

$$\mu(x) = \frac{|H_nB(x)|}{|H_nB(0)|} M_B(x) - \frac{|H_nA(x)|}{|H_nA(0)|} M_A(x) \tag{6}$$

where $\mu(x)$ is the magnetic moment per formula unit obtained from the cation distribution Equations (3) and (4) using the ionic magnetic moments of Fe$^{3+}$, Co$^{2+}$, and Al$^{3+}$ with the respective values 5 $\mu_B$, 3 $\mu_B$, and 0 $\mu_B$ and $|H_nB(x)|$ and $|H_nA(x)|$ are magnitudes of the average magnetic fields for the B and A sites, respectively. It is assumed that the relative saturation magnetization per formula unit $\frac{m_B(x)}{m_B(0)}$ at 300 K is equal to $\frac{\mu(x)}{\mu_B(0)}$. The values of the magnetic moment per formula unit $\eta_B^M \approx \mu(x)$ as a function of $x$ were determined from Equation (6) using the values of the nuclear magnetic fields obtained at 300 K from the Mössbauer results (Table III), and the same is displayed in Figure 5. There is a very good agreement among values of the unit $\eta_B^M(x)$ obtained from the Mössbauer data, $\eta_B(x)$, from the magnetization measurements, and $\eta_B^N(x)$ obtained from Néel’s model, as shown in Figure 5 for $x = 0.0$ to 0.8, confirming a collinear ferrimagnetic structure. This is further supported by the fact that decreasing $T_C$ with increasing $x$ is found to be nearly linear for $x = 0.0$ to 1.0. It is interesting to note that from a comparison of the magnetization and Mössbauer results for ceramically prepared CoFe$_{2-x}$Al$_x$O$_4$ [31] with the present sol-gel method prepared samples for the same series, interesting observations have been made. The sol-gel method provides nano particles in the system, which changes the magnetic ordering...
of the samples. For example, ceramically prepared samples \cite{31} display non-collinear ferromagnetic structure (canting) for $x = 0.0$ to $0.6$, whereas sol-gel prepared samples display Néel’s ferrimagnetic structure for the same samples. Magnetic moments observed for sol-gel prepared samples are rather much smaller than ceramically prepared samples, possibly due to nano size particles. Another unusual behavior observed in sol-gel samples for $x = 0.6$ to $1.0$, namely an increasing paramagnetic quadrupole doublet superimposed on hyperfine fields, is not seen in the ceramically prepared samples of $x = 0.6$ to $1.0$. Possibly this may also be attributed to nano particle size behavior in the sol-gel prepared samples. This may indicate either superparamagnetic behavior or uniaxial anisotropy introduced by magnetic Co$^{2+}$ ions, which would need further measurements of the low field a.c. susceptibility and external high field Mössbauer studies, which is beyond the scope of our available facility.

From the above results presented here, we propose that a peculiar magnetic behavior is displayed by our CoFe$_{2-x}$Al$_x$O$_4$ nanoparticles. In addition, a non-collinearity of the ferrimagnetic sub-lattice which was observed is mainly a surface effect.

IV. CONCLUSION

Nanocrystalline cobalt aluminum ferrites have been prepared with different grain sizes that decrease as the non-magnetic Al content increases. The magnetization decreases with increasing Al content, the reason is evident from the observed Mössbauer results, too. From the VSM and Mössbauer analysis we can say that in the lower dimension particles of a few nanometers, it is very difficult to maintain the ferrimagnetic nature. Hence, magnetic properties of Al substituted Co-ferrite depend on both the particle size and on the type of material.

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References

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