Hyperfine Interact (2016) 237:15
DOI 10.1007/s10751-016-1215-7

Comparative study of Aliskerovo, Anyujskij, Sikhote-Alin and Sterlitamak iron meteorites using Mössbauer spectroscopy

M. V. Goryunov[1,2] · M. I. Oshtrakh[1,2] · A. V. Chukin[3] · V. I. Grokhovsky[1] · V. A. Semionkin[1,2]

Abstract A comparative study of Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites was carried out using Mössbauer spectroscopy with a high velocity resolution as well as using metallography, scanning electron microscopy with energy dispersive spectroscopy and X-ray diffraction. Different numbers of spectral components were found in the Mössbauer spectra of Sikhote-Alin IIAB and Anyujskij IIAB and in the spectra of Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites. The values of hyperfine field at the ^{57}Fe nuclei obtained for spectral components were related to α-Fe(Ni, Co), α_2-Fe(Ni, Co) and γ-Fe(Ni, Co) phases with variations in Ni concentration.

Keywords Mössbauer spectroscopy · Iron meteorites · Hyperfine field · Phase composition

1 Introduction

Iron meteorites belong to differentiated meteorites consisting of Fe-Ni-Co alloy with possible inclusions of minor compounds such as iron-nickel phosphides and iron sulphides

This article is part of the Topical Collection on *Proceedings of the International Conference on the Applications of the Mössbauer Effect (ICAME 2015), Hamburg, Germany, 13–18 September 2015*

✉ M. I. Oshtrakh
oshtrakh@gmail.com

[1] Department of Physical Techniques and Devices for Quality Control, Institute of Physics and Technology, Ural Federal University, Ekaterinburg, 620002, Russian Federation

[2] Department of Experimental Physics, Institute of Physics and Technology, Ural Federal University, Ekaterinburg, 620002, Russian Federation

[3] Department of Theoretical Physics and Applied Mathematics, Institute of Physics and Technology, Ural Federal University, Ekaterinburg, 620002, Russian Federation

Published online: 18 February 2016

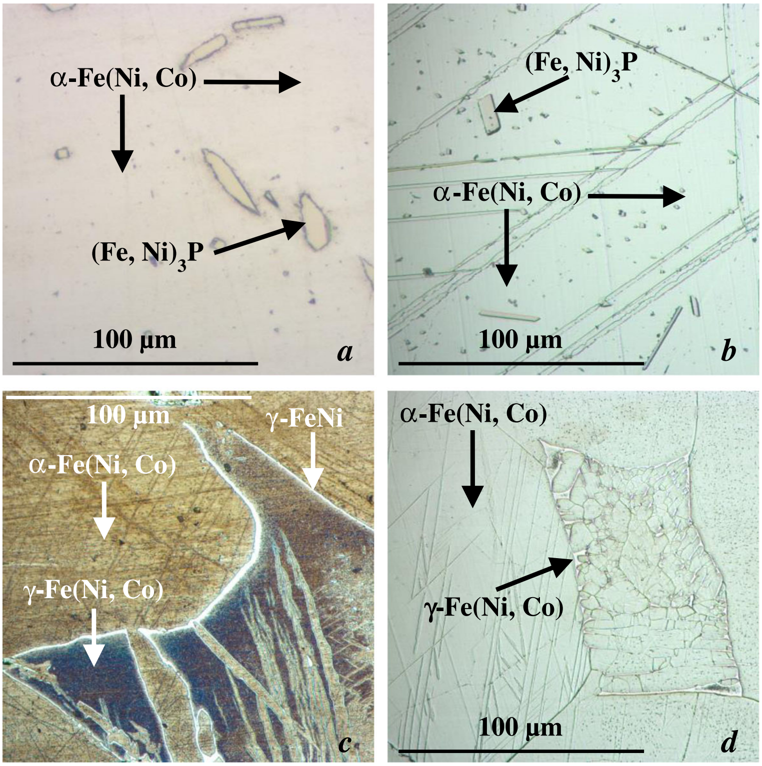

Fig. 1 Optical microphotographs of the iron meteorites slices: Sikhote-Alin IIAB (**a**), Anyujskij IIAB (**b**), Aliskerovo IIIE-an (**c**) and Sterlitamak IIIAB (**d**)

mainly [1]. Metallic iron may consist of b.c.c. α-Fe(Ni, Co) and α_2-Fe(Ni, Co) phases and f.c.c. γ-Fe(Ni, Co) phase (kamacite, martensite and taenite, respectively). Concentration of Ni in these phases does not exceed ∼7 at.% for α-phase, is in the ranges of ∼10–25 at.% for α_2-phase and of ∼29–50 at.% for γ-phase (the ordered γ-FeNi with 50 at.% of Ni is tetrataenite). Moreover, Ni and Co concentration may vary within the single phase. Variations in the phase compositions and Ni and Co concentration are the result of iron meteorites crystallization from melt with extremely slow cooling, further shock effects and reheating in the space. Therefore, it is not possible to reproduce extraterrestrial Fe-Ni-Co alloys in the terrestrial conditions while some features of meteorite metallic iron may be useful for new alloys development. Mössbauer spectroscopy is a useful tool for study iron meteorites (see, for instance, [2–5]). Therefore, we have applied Mössbauer spectroscopy to study some iron meteorites in order to evaluate the relationship of the hyperfine parameters and metal phases in meteorites with variations in Ni concentration [6, 7]. In this work four iron meteorites such as Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB were chosen for comparative study using Mössbauer spectroscopy.

2 Experimental

Slices of iron meteorites Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB were prepared for metallographic and scanning electron microscopy (SEM)

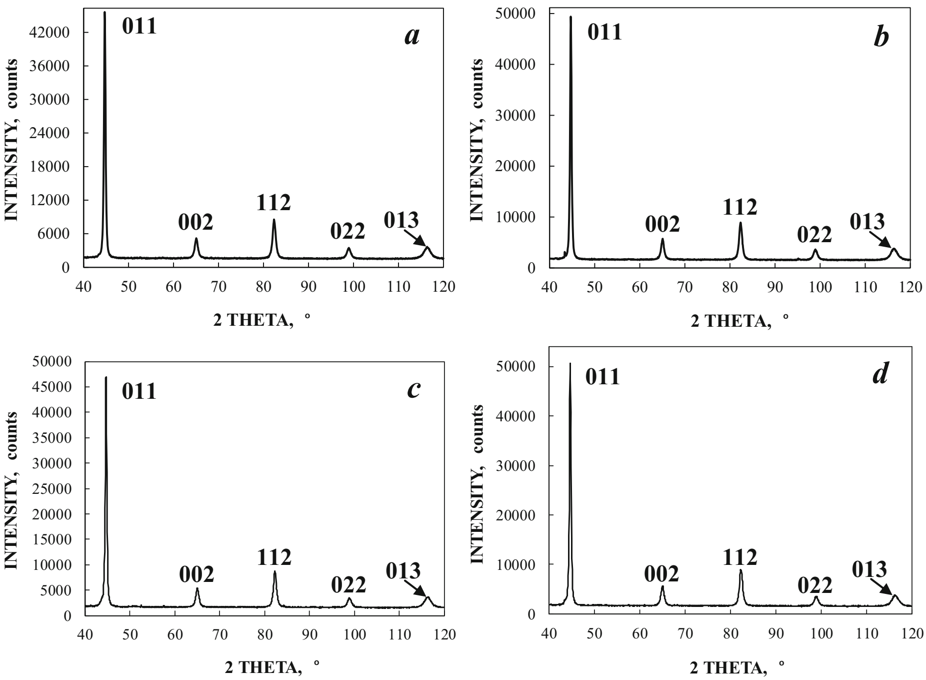

Fig. 2 X-ray diffraction patterns of the iron meteorites metallic alloy: Sikhote-Alin IIAB (**a**), Anyujskij IIAB (**b**), Aliskerovo IIIE-an (**c**) and Sterlitamak IIIAB (**d**)

analysis. Then thin powders of each meteorite metallic iron alloys were mechanically prepared from the fragments surfaces for X-ray diffraction (XRD) study. Then powdered samples were glued on aluminum foil free from iron for Mössbauer spectroscopy. The sample thickness was in the range of 6–8 mg Fe/cm^2.

Metallographic analysis was done using Axiovert 40 MAT optical microscope (Carl Zeiss). SEM analysis with energy dispersive spectroscopy (EDS) was carried out using ΣIGMA VP electron microscope (Carl Zeiss). X-ray diffraction was measured using XRD–7000 powder diffractometer (Shimadzu) operated at 40 kV and 30 mA with Ni-filtered CuK$_\alpha$ radiation. For detailed X-ray line profile analysis, step-scan data (2Θ step of 0.03° and counting time of 25 s) were recorded for these samples in the 2Θ range of 40–120°. Mössbauer spectra were measured using an automated precision Mössbauer spectrometric system built on the base of the SM-2201 spectrometer with a saw-tooth shape velocity reference signal formed by the digital-analog converter using discretization of 2^{12} (quantification using 4096 steps). Details and characteristics of this spectrometer and the system were given elsewhere [8–10]. The 1.8×10^9 Bq ^{57}Co(Rh) source (Ritverc GmbH, St. Petersburg) was used at room temperature. The Mössbauer spectra were measured in transmission geometry with moving absorber in the cryostat at 295 K and recorded in 4096 channels. For their analysis, spectra were converted into 1024 channels by a consequent summation of four neighboring channels to increase a signal-to-noise ratio. The spectra were computer fitted with the least squares procedure using UNIVEM-MS program with a Lorentzian line shape. The spectral parameters such as: isomer shift, δ, quadrupole shift for magnetically split spectra, ΔE_Q, magnetic hyperfine field, H_{eff}, line width, Γ, relative subspectrum area,

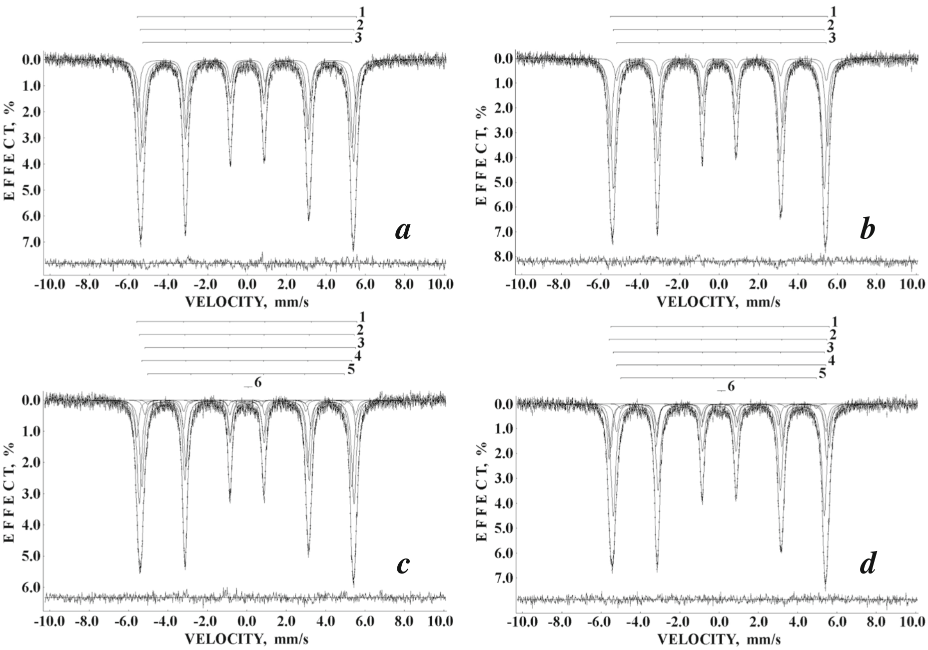

Fig. 3 Mössbauer spectra of the iron meteorites: Sikhote-Alin IIAB (**a**), Anyujskij IIAB (**b**), Aliskerovo IIIE-an (**c**) and Sterlitamak IIIAB (**d**) measured at room temperature. Indicated components are the results of the best fits. Differential spectra are shown below

A, and statistical quality of the fit, χ^2, were determined. An instrumental (systematic) error for each spectrum point was ± 0.5 channel (the velocity scale), the instrumental (systematic) error for the hyperfine parameters was ± 1 channel. If an error calculated with the fitting procedure (fitting error) for these parameters exceeded the instrumental (systematic) error we used the larger error instead. Values of δ are given relative to α-Fe at 295 K.

3 Results and discussion

Metallographic analysis of Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB (Fig. 1) showed the presence of α-Fe(Ni, Co) phase with rhabdite $(Fe, Ni)_3P$ microcrystals in kamacite matrix in Sikhote-Alin IIAB and Anyujskij IIAB while Aliskerovo IIIE-an and Sterlitamak IIIAB metallic iron consists of α-Fe(Ni, Co) and γ-Fe(Ni, Co) phases and plessite structures ($\alpha/\alpha_2 + \gamma$ phases).

SEM analysis confirmed these phases composition in the studied iron meteorites. EDS data demonstrated an average Ni and Co concentration of ~5 at.% and ~1 at.%, respectively, in Sikhote-Alin IIAB and Anyujskij IIAB α-phase. Concentration of Ni was found in the range of ~4–7 at.% for the grains of α phase and ~7–9 at.% probably for α_2 phase while that for γ phase was observed in the range of ~32–35 at.% and 50 at.% for tetrataenite rims of grains in Aliskerovo IIIE-an metal. Concentration of Ni in Sterlitamak IIIAB was found of ~6.5–7 at.% for the grains of α phase and ~7–8 at.% probably for α_2 phase while that for γ phase was observed in the range of ~30–34 at.%. The concentration of Co was in the range of ~0.5–1 at.%. XRD patterns of the samples of Sikhote-Alin IIAB, Anyujskij IIAB,

Table 1 Mössbauer parameters of Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites

Sample	Γ, mm/s	δ, mm/s	ΔE_Q, mm/s	H_{eff}, kOe	A, %	Component[a]
Sikhote-Alin	0.240 ± 0.040	0.011 ± 0.020	−0.034 ± 0.020	345.1 ± 0.6	19	α−Fe(Ni, Co) (1)
	0.265 ± 0.040	−0.004 ± 0.020	−0.010 ± 0.020	336.5 ± 0.6	40	α−Fe(Ni, Co) (2)
	0.313 ± 0.040	−0.001 ± 0.020	0.014 ± 0.020	329.7 ± 0.6	41	α−Fe(Ni, Co) (3)
Anyujskij	0.270 ± 0.040	0.010 ± 0.020	−0.037 ± 0.031	342.3 ± 0.6	36	α−Fe(Ni, Co) (1)
	0.287 ± 0.040	−0.015 ± 0.020	−0.002 ± 0.032	332.5 ± 0.6	56	α−Fe(Ni, Co) (2)
	0.255 ± 0.040	0.083 ± 0.020	0.082 ± 0.020	330.0 ± 0.8	8	α−Fe(Ni, Co) (3)
Aliskerovo	0.234 ± 0.040	0.015 ± 0.020	−0.024 ± 0.020	347.1 ± 0.6	14	α_2−Fe(Ni, Co) (1)
	0.269 ± 0.040	0.003 ± 0.020	−0.020 ± 0.020	338.6 ± 0.6	43	α−Fe(Ni, Co) (2)
	0.233 ± 0.040	0.036 ± 0.020	0.274 ± 0.028	332.3 ± 1.1	5	α−Fe(Ni, Co) (3)
	0.259 ± 0.040	0.001 ± 0.020	0.003 ± 0.020	330.9 ± 0.6	35	α−Fe(Ni, Co) (4)
	0.233 ± 0.096	0.006 ± 0.020	−0.096 ± 0.048	310.1 ± 2.1	2	γ−Fe(Ni, Co) (5)
	0.664 ± 0.246	0.071 ± 0.069	–	–	1	γ−Fe(Ni, Co) (6)
Sterlitamak	0.233 ± 0.040	0.057 ± 0.020	−0.007 ± 0.020	344.7 ± 0.6	16	α_2−Fe(Ni, Co) (1)
	0.239 ± 0.040	−0.031 ± 0.020	−0.046 ± 0.020	343.7 ± 0.6	20	α_2−Fe(Ni, Co) (2)
	0.295 ± 0.040	0.001 ± 0.020	−0.024 ± 0.020	333.4 ± 0.6	50	α−Fe(Ni, Co) (3)
	0.263 ± 0.040	0.024 ± 0.020	0.182 ± 0.020	330.7 ± 0.7	11	α−Fe(Ni, Co) (4)
	0.238 ± 0.071	0.243 ± 0.020	−0.534 ± 0.041	309.1 ± 1.6	2	γ−Fe(Ni, Co) (5)
	0.352 ± 0.152	0.128 ± 0.050	–	–	1	γ−Fe(Ni, Co) (6)

[a]Numbers in parenthesis correspond to components numbers in Fig. 3

Aliskerovo IIIE-an and Sterlitamak IIIAB are shown in Fig. 2. XRD demonstrated also the presence of kamacite in Sikhote-Alin IIAB and Anyujskij IIAB iron meteorites while small amount of taenite in addition to the main α-phase in Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites was found.

Mössbauer spectra of the iron meteorites Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB measured at room temperature and presented in 1024 channels are shown in Fig. 3. These spectra demonstrated similar asymmetric six-line patterns which cannot be fitted well using one magnetic sextet. The best fits of these spectra showed different results for Sikhote-Alin IIAB and Anyujskij IIAB iron meteorites and Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites. The Mössbauer spectra of Sikhote-Alin IIAB and Anyujskij IIAB iron meteorites were fitted using three magnetic sextets while the spectra of Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites were fitted using five magnetic sextets and one paramagnetic singlet. Parameters of the Mössbauer spectra are collected in Table 1. The values of H_{eff} for magnetic sextets obtained for Sikhote-Alin IIAB and Anyujskij IIAB iron meteorites were related to α phase with variations in Ni concentration. Similarly, the values of H_{eff} for magnetic sextets 1–4 in the Mössbauer spectra of Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites were related to α_2 and α phases. However, the smallest value of H_{eff} for magnetic sextet 5 was related to γ phase. Mössbauer parameters for the minor singlet 6 were within the errors for two meteorites; however, the errors were very large due to a very small signal-to-noise ratio for this peak in both spectra. Nevertheless, we can consider a relation of this singlet to small amount of paramagnetic γ phase with Ni concentration in the range of ∼29–33 at.% (see, for instance, [11, 12]).

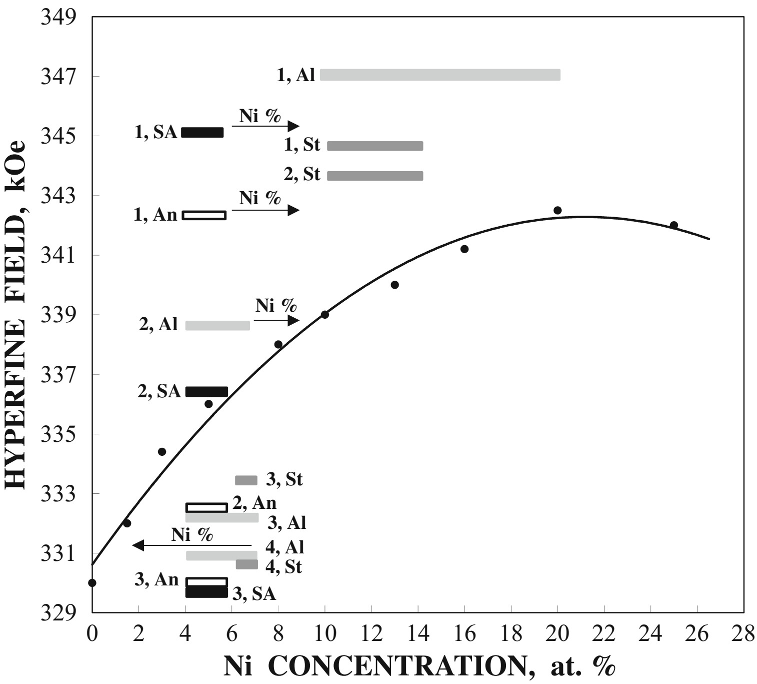

Fig. 4 Variation of the average hyperfine field at the ^{57}Fe vs. Ni concentration in Fe-Ni alloys at room temperature (•) taken from [13] and ranges of Ni concentrations for α-Fe(Ni, Co) and α_2-Fe(Ni, Co) in Sikhote-Alin IIAB (■, SA), Anyujskij IIAB (□, An), Aliskerovo IIIE-an (, Al) and Sterlitamak IIIAB (, St) iron meteorites at the corresponding obtained values of the hyperfine field (numbers 1–4 indicates the numbers of spectral components in Fig. 3 and Table 1). Arrows indicate the direction of suggested change in Ni concentration for given value of the hyperfine field

It is interesting to compare the early data by Vincze et al. [13] on the relationship of the average hyperfine field at the ^{57}Fe in α-Fe(Ni) alloy and Ni concentration with obtained H_{eff} values for individual components related to α-Fe(Ni, Co) phase in iron meteorites. Dependence of the average hyperfine field at the ^{57}Fe versus Ni concentration in the range between 0 and 25 at.% for α-Fe(Ni) alloys is shown in Fig. 4. The values of H_{eff} for spectral components of the Mössbauer spectra of Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites related to α and α_2 phases are shown in Fig. 4 with the corresponding ranges of Ni concentration. Using this data we can suppose that spectral components 1 in the Mössbauer spectra of Sikhote-Alin IIAB and Anyujskij IIAB iron meteorites could be related to α phase with higher Ni concentration (may be to α_2 phase?) while component 3 in these spectra as well as component 4 in the Mössbauer spectra of Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites could be related to α phase with smaller Ni concentration. In spite of the absence of α_2-Fe(Ni, Co) phase in Sikhote-Alin IIAB and Anyujskij IIAB iron meteorites some changes in Ni concentration are possible in the ^{57}Fe local microenvironment (within several coordination spheres) with distribution of this type of microenvironment through the meteoritic alloy. Microscopic techniques and EDS cannot distinguish this difference while Mössbauer spectroscopy is very sensitive to the ^{57}Fe local microenvironment. Similarly, there is a possibility of the presence of the ^{57}Fe local microenvironment with smaller Ni concentration than average data obtained by EDS.

4 Conclusion

Comparative study of Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites using Mössbauer spectroscopy demonstrated the best fits of the spectra using different numbers of components. These components could be related to α and γ phases with different Ni concentrations. Within the analysis carried out we can suppose that metallic iron alloy in Sikhote-Alin IIAB and Anyujskij IIAB meteorites (both are coarse octahedrites) consists of α-Fe(Ni, Co) phase with variations in Ni concentration while that in Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites (both are medium octahedrites) consists of α-Fe(Ni, Co) and α_2-Fe(Ni, Co) phases with variations in Ni concentration and small amount of γ-Fe(Ni, Co) phase in the magnetic and, probably, paramagnetic states. The contribution of spectral components corresponding to suggested phases to the Mössbauer spectra of studied meteorites appeared to be different that may be a result of different thermal history of Sikhote-Alin IIAB, Anyujskij IIAB, Aliskerovo IIIE-an and Sterlitamak IIIAB iron meteorites and different parent bodies for coarse and medium octahedrites. However, further investigations are required.

Acknowledgments This work was supported by the Ministry of Education and Science of Russian Federation (basic financing for the Project №. 2085) and Act 211 Government of the Russian Federation, contract No. 02.A03.21.0006.

References

1. Buchwald, V.F.: Handbook of Iron Meteorites, p. 1418. University of California Press, Berkeley (1975)
2. Scorzelli, R.B.: Hyperfine Interact. **66**, 249 (1991)
3. Paduani, C., Pérez, C.A.S., Ardisson J.D.: Braz. J. Phys. **35**, 667 (2005)
4. Cabanillas, E.D., Palacios, T.A.: Planet. Space Sci. **54**, 303 (2006)
5. Dos Santos, E., Gattacceca, J., Rochette, P., Scorzelli, R.B., Fillion, G.: Phys. Earth Planet. Inter. **242**, 50 (2015)
6. Oshtrakh, M.I., Milder, O.B., Grokhovsky, V.I., Semionkin, V.A.: Hyperfine Interact. **158**, 365 (2004)
7. Grokhovsky, V.I., Oshtrakh, M.I., Milder, O.B., Semionkin, V.A.: Bull. Russ. Acad. Sci. Phys. **69**, 1710 (2005)
8. Oshtrakh, M.I., Semionkin, V.A., Milder, O.B., Novikov, E.G.: J. Radioanal. Nucl. Chem. **281**, 63 (2009)
9. Semionkin, V.A., Oshtrakh, M.I., Milder, O.B., Novikov, E.G.: Bull. Rus. Acad. Sci.: Phys. **74**, 416 (2010)
10. Oshtrakh, M.I., Semionkin, V.A.: Spectrochim. Acta A: Mol. Biomol. Spectrosc. **100**, 78 (2013)
11. Dunlap, R.A.: Hyperfine Interact. **110**, 209 (1997)
12. Baldokhin, Yu.V., Tcherdyntsev, V.V., Kaloshkin, S.D., Kochetov, G.A., Pustov, Yu.A.: J. Mag. Mag. Mater. **203**, 313 (1999)
13. Vincze, I., Campbell, I.A., Meyer, A.J. Solid State Commun. **15**, 1495 (1974)