

Article

Thermodynamics of Phase Equilibria in the CoO–BaO–Fe₂O₃ System

Natalia Tsapko ¹, Halyna Shabanova ², Serhii Logvinkov ³, Athanasios G. Mamalis ^{4,*}, Volodymyr Nerubatskyi ⁵  and Edvin Hevorkian ^{6,*}

¹ Scientific Research Institution “Ukrainian Scientific Research Institute of Ecological Problems”, 6 Yenina Yevheniya St., 61165 Kharkiv, Ukraine; tsapko@niiep.kharkov.ua

² Department of Ceramic Technology, Refractories, Glass, and Enamels, National Technical University “Kharkiv Polytechnic Institute”, 2 Kyrpychova St., 61002 Kharkiv, Ukraine; gala-shabanova@ukr.net

³ Department of Occupational Health and Safety, O. M. Beketov National University of Urban Economy in Kharkiv, 17 Chornoglazivska St., 61002 Kharkiv, Ukraine; sergii.logvinkov@m.hneu.edu.ua

⁴ Project Center for Nanotechnology and Advanced Engineering, 60037 Athens, Greece

⁵ Department of Electrical Energetics, Electrical Engineering and Electromechanics, Ukraine State University of Railway Transport, 7 Feuerbach Sq., 61050 Kharkiv, Ukraine; nerubatskyi@kart.edu.ua

⁶ Department of Mechanical Engineering and Automation, Faculty of Production Engineering, University of Life Sciences in Lublin, 28 Głęboka St., 20-612 Lublin, Poland

* Correspondence: mamalis@central.ntua.gr (A.G.M.); edwin.hevorkian@up.lublin.pl (E.H.)

Abstract

The work presents a thermodynamic analysis of phase equilibria in the subsolidus region of the three-component oxide system CoO–BaO–Fe₂O₃. The relevance of the study is due to the growing interest in ceramic ferrites with specified magnetic and electromagnetic properties, which are used in the creation of functional composite materials. The aim of the work was to establish thermodynamically stable binary and ternary phase combinations in the CoO–BaO–Fe₂O₃ system based on the analysis of solid-phase exchange reactions without taking into account ternary oxide compounds. This analysis represents a simplified thermodynamic model that considers only binary oxide compounds and excludes ternary ferrite phases. Thermodynamic calculations of Gibbs energy changes for model reactions of the type “2 = 2” were performed in the temperature range 1000–1800 K using the temperature dependencies of the enthalpies and entropies of compounds. To resolve contradictions arising from the analysis of the stability of individual conjugates, the method of conjugating exchange reactions with a transition to “3 = 2” type interaction mechanisms was applied. As a result of triangulation, nine thermodynamically stable binary combinations of compounds and ten stable triple phase combinations corresponding to elementary triangles of the subsolidus structure of the system were identified. The predisposition of the CoFe₂O₄–BaFe₁₂O₁₉ compound to destabilization is demonstrated, and its structural and phase stabilization due to the formation of an equilibrium three-phase combination of CoFe₂O₄–CoO–BaFe₁₂O₁₉ is substantiated. A general rule has been formulated for analyzing the thermodynamic stability of phase combinations in exchange reactions of the type “3 = 2”. The results obtained provide a physicochemical basis for predicting the phase composition of ferrite materials and composites in any concentration range of the CoO–BaO–Fe₂O₃ system and can be used in the development of technologies for the reaction synthesis of new ceramic ferrites.

Keywords: subsolid structure; phase equilibria; thermodynamic analysis; Gibbs energy; ceramic ferrites



Academic Editor: Roumiana P. Stateva

Received: 26 March 2026

Revised: 11 May 2026

Accepted: 11 June 2026

Published: 1 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Ferrites based on the CoO–BaO–Fe₂O₃ system represent an important class of functional oxide materials, combining structural and phase diversity with a wide range of magnetic and electromagnetic properties. Interest in such materials has grown significantly in recent years due to developments in microwave technology, electronics, electromagnetic shielding systems, data storage devices, and multiferroic components.

The CoO–BaO–Fe₂O₃ system is the physicochemical basis for the formation of at least two key families of ferrites—spinel cobalt ferrites (CoFe₂O₄) and barium hexaferrites (BaFe₁₂O₁₉)—as well as more complex Y-, Z-, and W-type ternary oxides (Ba₂Co₂Fe₁₂O₂₂, Ba₃Co₂Fe₂₄O₄₁, etc.). Each of these phases is characterized by a specific type of crystal structure, the distribution of cations across the lattice nodes, and, as a result, individual magnetic parameters—coercive force, magnetic anisotropy, saturation magnetization, and resonance characteristics in the microwave range.

In addition to crystallochemical factors, the functional properties of ferrites in the CoO–BaO–Fe₂O₃ system are largely determined by the thermodynamic stability of phases and phase combinations in the subsolidus region. It is in this temperature range that the actual phase composition of ceramic materials is formed during solid-phase synthesis, sintering, and reaction-based formation of composites.

Cobalt ferrite CoFe₂O₄ is a hard magnetic material with a spinel structure, high coercive force, and pronounced magnetoelastic coupling, which makes it promising for sensor systems, magnetostrictive devices, and wear-resistant magnetic components [1]. Spinel cobalt ferrites CoFe₂O₄ are characterized by pronounced cation inversion, which depends on the synthesis conditions and phase environment and directly affects magnetocrystallographic anisotropy, magnetostriction, and losses in the microwave range [2]. The presence of barium ferrite phases in equilibrium with spinel can lead to the redistribution of Co²⁺ and Fe³⁺ ions, changes in oxygen stoichiometry, and the formation of metastable configurations.

Hexaferrite BaFe₁₂O₁₉, which has a magnetoplumbite structure, is characterized by high magnetic anisotropy and thermal stability, but its phase stability in multicomponent systems significantly depends on the presence of cobalt-containing phases and on the thermodynamics of exchange reactions in the subsolidus. A number of studies [3,4] indicate that even small deviations from equilibrium phase combinations can lead to the formation of secondary phases or triple hexaferrites (W- and Z-type) with different electromagnetic characteristics [5,6].

Of particular interest are heterophase combinations of spinel and hexaferrite phases, which are considered promising materials for microwave absorption and electromagnetic shielding. The compounds Ba₂Co₂Fe₁₂O₂₂, BaCo₂Fe₁₆O₂₇, and Ba₃Co₂Fe₂₄O₄₁ belong to the triple oxide phases of the BaO–CoO–Fe₂O₃ system and represent the Y-, W-, and Z-types of hexaferrites, respectively [7,8]. These compounds are characterized by a complex hexagonal crystal structure formed by alternating structural units, which determines their specific magnetic and electromagnetic properties. The literature shows that their formation and phase stability significantly depend on the conditions of solid-phase synthesis and the thermodynamics of subsolidus exchange reactions [9]. Particular interest in these phases is associated with the possibility of their coexistence with spinel and M-type hexaferrite phases, which opens up prospects for the creation of heterophase and composite ferrite materials. The effectiveness of such materials is determined not only by the individual properties of the phases but also by the thermodynamic stability of their coexistence, which, in turn, is associated with the subsolidus structure of the corresponding oxide system. In addition to thermodynamic factors, topological and structural characteristics of crystal frameworks may influence reaction pathways and phase stability in multicomponent ferrite systems. A brief discussion concerning the relationship between topology and

thermodynamics in chemical reactions has been added in accordance with previous studies reported in the literature.

Methods for producing CoO–BaO–Fe₂O₃ ferrites include traditional solid-phase synthesis, sol–gel technologies, autocatalytic combustion, co-precipitation, hydrothermal and sonochemical methods. Solid-phase synthesis remains the basis for industrial production of ferrites, but it requires high temperatures and long isothermal holding times, which can lead to grain coarsening and the appearance of secondary phases. Modern chemical methods (sol–gel, co-precipitation) allow obtaining highly homogeneous powders with controlled particle size and reduced phase formation temperature, which is especially important for the synthesis of complex triple hexaferrites [10,11].

Controlling the phase composition (spinel–hexaferrite–triple oxides) requires an understanding not only of thermodynamic preferences, but also of phase formation kinetics. Traditionally, a combined approach is used in various three-component oxide systems, which includes thermodynamic optimization followed by experimental validation of phase diagrams, thereby increasing the accuracy of predicting stable combinations.

Despite a significant number of studies devoted to the synthesis and properties of individual ferrite compounds, systematic investigations of phase equilibria and thermodynamic stability of binary and ternary combinations of compounds in the CoO–BaO–Fe₂O₃ system are practically absent. Most published phase diagrams are fragmentary or empirical in nature and do not take into account the possibility of competition between exchange reactions and conjugate interaction mechanisms in the subsolidus region. The present study does not aim to construct a complete equilibrium phase diagram including all ternary ferrite compounds. Instead, the objective is to analyze the thermodynamic stability of binary phase equilibria as an independent subsolidus approximation that may be relevant for intermediate stages of solid-state synthesis and metastable phase formation.

In this regard, the application of thermodynamic analysis of solid-phase exchange reactions of the “2 = 2” type and their conjugation into “3 = 2” type mechanisms appears to be a reasonable and promising approach, allowing the identification of hidden factors of stabilization or destabilization of phase combinations and the formation of a physico-chemical basis for predicting the phase composition of ferrite materials in a wide range of compositions and temperatures.

2. Materials and Methods

The estimated assessment of the degree of complexity of the subsolid structure of three-component physicochemical systems was carried out using the method [12]. The calculations took into account the temperature dependencies of the enthalpy and entropy changes in the corresponding compounds. The calculations were performed with an accuracy of 1 kJ/mol and then rounded to 1 kJ/mol for ease of analysis. The thermodynamic parameters marked as calculated values were estimated using additive thermodynamic approximation methods based on structurally related ferrite compounds and oxide components. The initial thermodynamic data are presented in Table 1. All thermodynamic calculations were performed under the assumption of constant pressure corresponding to standard atmospheric pressure ($P = 1$ atm). The estimation procedure was based on additive thermodynamic approximations using reference thermodynamic data of structurally related ferrite and oxide compounds.

Table 1. Initial thermodynamic data.

Compound Formula	$-\Delta H^0_{298},$ kJ/mol	$\Delta S^0_{298},$ J/(mol·K)	$C_p = a + b \cdot T + c \cdot T^2, \text{ J/(mol·K)}$		
			a	$b \cdot 10^3$	$-c \cdot 10^{-5}$
CoO	238.9	52.97	48.28	8.535	1.67
BaO	558.15	70.29	53.30	4.35	8.3
Fe ₂ O ₃	821.36	89.96	98.28	9.04	14.85
BaFe ₁₂ O ₁₉	5886.09	609.19	348.60	1168.82	–
BaFe ₂ O ₄	1282.81	158.99	172.38	20.88	5.94
Ba ₂ Fe ₂ O ₅	1763.97	229.07	295.03	–	51.09
Ba ₂ Fe ₆ O ₁₁	3752.80	437.4	398.94	119.50	59.91
BaCoO ₂ *	837.13	123.08	78.99	38.34	4.49
CoFe ₂ O ₄	1087.4	134.7	131.8	141.42	–
Ba ₂ Co ₂ Fe ₁₂ O ₂₂ *	6848.23	785.98	812.71	203.71	140.65
BaCo ₂ Fe ₁₆ O ₂₇ *	7987.63	895.36	1029.37	151.06	214.45
Ba ₃ Co ₂ Fe ₂₄ O ₄₁ *	12,609.45	1396.22	1566.51	255.75	314.43

*—calculated values.

3. Results and Discussion

The presence of only one compound in each of the two double subsystems of the CoO–BaO–Fe₂O₃ system under study (CoFe₂O₄ and BaCoO₂ in the CoO–Fe₂O₃ and BaO–CoO subsystems, respectively) determines the low degree of complexity of its subsolidus structure. For a complete description of all two-phase equilibria, it is necessary to compile five equations of solid-phase exchange reactions of the type “2 = 2” (two initial compounds and two compounds in the reaction products). We have compiled all the necessary data for such reactions and determined for each of them the dependence of Gibbs energy change (ΔG) on temperature (T) in the range from 1000 to 1800 K. Table 2 contains only the calculation results that determine the most significant positions for triangulation of the system under study. For the entire temperature range (1000–1800 K), the reactions were calculated as solid-phase reactions due to the lack of reliable data on the melting or decomposition temperatures of some compounds of the system under study, as well as on the compositions and temperatures of eutectics between them. The presence of three triple compounds in the system under study classifies it as complex, since taking them into account requires the creation of 20 equations of solid-phase reactions of the type “2 = 2.” Therefore, the results of calculations for reactions involving triple oxide compounds have been omitted from this study.

Table 2. Values of Gibbs free energy change with temperature for model reactions of the CoO–BaO–Fe₂O₃ system (C—CoO, B—BaO, F—Fe₂O₃).

No.	Reaction	$\Delta G, \text{ kJ/mol at } T, \text{ K}$				
		1000	1200	1400	1600	1800
1	CoF + BF ₆ = BCo + 7F	−2021	−2099	−2178	−2257	−2336
2	Co + BF ₆ = BCo + 6F	463	556	683	846	1046
3	3Co + 2B ₂ F ₃ = 3BCo + BF ₆	−159	−206	−282	−389	−527
4	5Co + 6BF = 5BCo + BF ₆	−1203	−1255	−1336	−1450	−1598
5	11Co + 6B ₂ F = 11BCo + BF ₆	−1630	−1560	−1513	−1494	−1508
6	17Co + 6B ₃ F = 17BCo + BF ₆	−5783	−5875	−6004	−6173	−6387
7	20Co + 3B ₇ F ₂ = 20BCo + BF ₆	−1228	−1295	−1401	−1548	−1738
8	29Co + 6B ₅ F = 29BCo + BF ₆	−1047	−1021	−1025	−1060	−1127

To simplify the analysis of the results of calculations $\Delta G = f(T)$, it is advisable to start with reactions that interconnect compounds near the side of the concentration triangle of

the system with the smallest number of compounds. In the CoO–Fe₂O₃ subsystem, there is one binary compound, CoFe₂O₄, and in the immediate vicinity of the corresponding side of the concentration triangle (including on it), there are points of composition of compounds: CoFe₂O₄, BaFe₁₂O₁₉, BaCoO₂, and Fe₂O₃. The exchange reaction No. 1 (Table 2) links the compounds mentioned above. The negative sign of the ΔG values for this reaction indicates its preference for proceeding in the forward direction (left to right) and the thermodynamic stability of the combination of BaCoO₂ with Fe₂O₃ compared to the initial combination of CoFe₂O₄ with BaFe₁₂O₁₉. However, the results of calculations of ΔG values for reaction No. 2 (Table 2) contradict this conclusion, as they indicate the instability of BaCoO₂ combinations with Fe₂O₃ compared to the combination of CoO with BaFe₁₂O₁₉. This situation can be represented geometrically as the necessity of the existence of the BaCoO₂–Fe₂O₃ conjugate according to reaction No. 1 and, at the same time, the necessity of the existence of the CoO–BaFe₁₂O₁₉ conjugate, which intersects the BaCoO₂–Fe₂O₃ conjugate. Similar contradictions are found in the thermodynamic analysis of the subsolidus structure of physicochemical systems. To resolve the direct comparison of ΔG values for reactions No. 1 and No. 2, it is not enough to rely on the stability of BaCoO₂ in combination with Fe₂O₃, based on higher ΔG values for reaction No. 1 compared to reaction No. 2, as this is not confirmed by further analysis. In such situations, it is necessary to analyze more complex phase equilibria possible in three-component systems. According to Gibbs' phase rule, five phases can be in equilibrium in three-component systems, i.e., solid-phase reactions of the type "2 = 3" or "3 = 2" (two compounds in the starting reagents and three compounds in the reaction products, or vice versa) must be considered. The composition of such reactions and the calculation of the corresponding ΔG values are completely determined by the known equations and ΔG values for reactions of the type "2 = 2." In our case, algebraic summation of reaction equations No. 1 and No. 2 and their ΔG values (Table 2) leads to the reaction:



The reference values ΔG for reaction (1) ($\Delta G_{1000\text{ K}} = -1558$, $\Delta G_{1800\text{ K}} = -1290$ kJ/mol) indicate the stability of BaCoO₂ in combination with Fe₂O₃. However, for reactions of the type "2 = 3" or "3 = 2", there are many possible solutions, since their geometric image in the system is the intersection of a straight line segment defined by the points of composition of the compounds of a two-phase combination (BaCoO₂ and Fe₂O₃ in our case) with a triangle whose vertices are defined by the points of composition of the compounds of a three-phase combination (in our case, CoFe₂O₄, CoO, and BaFe₁₂O₁₉). Therefore, to answer the question about the thermodynamic stability of a three-phase combination according to equations of type (1), it is sufficient to show that among their set there are reactions with a positive value of ΔG . It is easy to see that the algebraic sum of Reaction (1) and the four reactions No. 2 (Table 2), i.e., No. 1 + 4 * No. 2, gives the reaction:



For Reaction (2), the ΔG values are positive above 1000 K, so the three-phase combination is thermodynamically stable, and there is a corresponding elementary triangle CoFe₂O₄–CoO–BaFe₁₂O₁₉ in the subsolidus structure. In fact, this situation means that the stability of the CoFe₂O₄–BaFe₁₂O₁₉ compound in the three-phase combination is maintained by the CoO–BaFe₁₂O₁₉ compound. It is obvious that increasing the stoichiometric multiplier (the multiplier before reaction equation No. 2 and the corresponding values of ΔG when algebraically summing the conjugate reactions No. 1 and No. 2 into a new interaction mechanism of the type "3 = 2") will ensure an increase in the positive values of ΔG of

Reaction (2), i.e., it will enhance the stabilization of the coexistence of the “weak” CoFe_2O_4 – $\text{BaFe}_{12}\text{O}_{19}$ combination. At the same time, the influence of combinatorics increases, as the probability of steric phase separation in a “weak” combination increases through contact with CoO , coexisting with both CoFe_2O_4 and $\text{BaFe}_{12}\text{O}_{19}$ in a three-phase combination according to Equation (2). Accordingly, when reactions No. 1 and No. 2 are thermodynamically coupled into a new solid-phase interaction mechanism of the “3 = 2” type (see Reaction (2)), structural and phase stabilization of the “weak” CoFe_2O_4 – $\text{BaFe}_{12}\text{O}_{19}$ conod in the subsolidus structure of the studied system occurs. The identified “weakness” or certain predisposition to destabilization of the CoFe_2O_4 – $\text{BaFe}_{12}\text{O}_{19}$ compound, in our opinion, manifests itself in the possibility of forming a triple oxide compound $\text{BaCo}_2\text{Fe}_{16}\text{O}_{27}$. The composition point of this compound belongs to the indicated tie-line, since the stoichiometric composition of the triple oxide corresponds to the oxide formula $2(\text{CoFe}_2\text{O}_4) \cdot \text{BaFe}_{12}\text{O}_{19}$. This is an important circumstance for the technological practice of reaction synthesis of heterophase ferrites, whose composition belongs to the CoFe_2O_4 – $\text{BaFe}_{12}\text{O}_{19}$ series, from starting reagents based on BaCoO_2 and Fe_2O_3 . At the same time, the possible thermodynamic stability of ternary ferrite phases does not eliminate the importance of analyzing binary equilibria because such equilibria may control intermediate reaction pathways, local metastable states, and heterophase configurations during solid-phase synthesis.

The above results of thermodynamic coupling of two three-phase reactions of the type “2 = 2” into a mechanism of interaction of the type “3 = 2” can be interpreted as a practical thermodynamic approach illustrated by a block diagram (Figure 1).

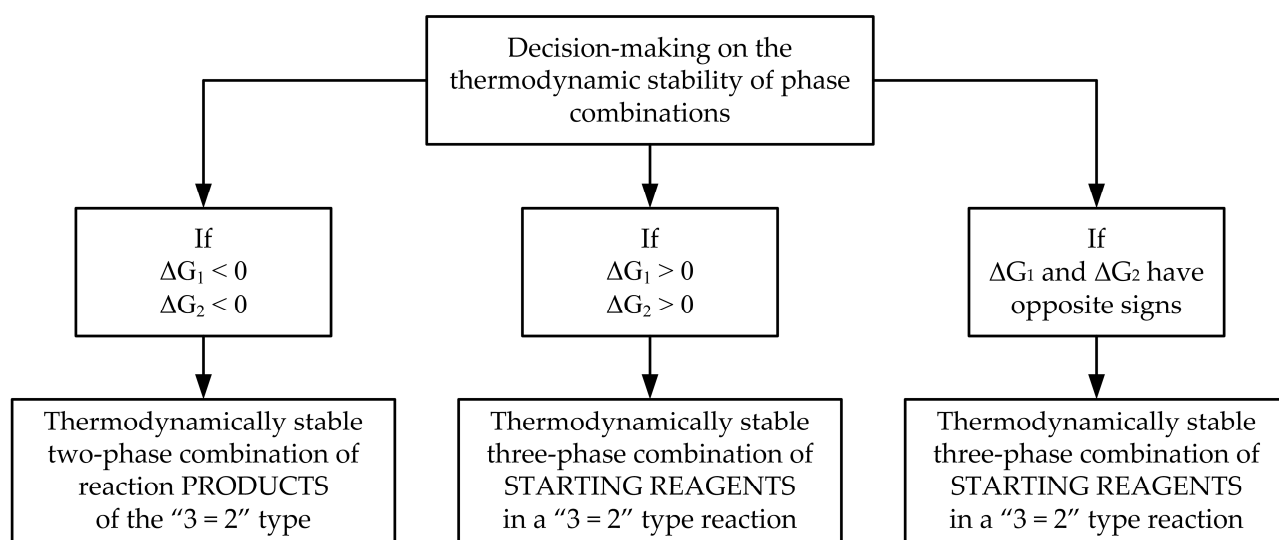


Figure 1. Block diagram of decision-making on the thermodynamic stability of phase combinations when coupling solid-phase exchange reactions of the “2 = 2” type into a “3 = 2” type interaction mechanism.

The formulated rule is important for analyzing the subsolidus structure of multicomponent physicochemical systems based on the results of thermodynamic calculations of solid-phase exchange reactions.

Reactions No. 3 and No. 4 (Table 2) test the thermodynamic stability of the two-phase combination of BaCoO_2 and $\text{BaFe}_{12}\text{O}_{19}$. For both reactions, the ΔG values are negative, so there is no competition when they are paired in a three-phase interaction mechanism, and the two-phase combination of reaction products of the “3 = 2” type is stable according to the above rule:



Due to the thermodynamic stability of the compounds in the reaction products (3), a corresponding $\text{BaCoO}_2\text{--BaFe}_{12}\text{O}_{19}$ phase is established in the subsolid structure of the system under study. Further triangulation of the $\text{CoO--BaO--Fe}_2\text{O}_3$ system is unavoidable for geometrical and topological reasons, since there are no other ways to close elementary triangles between the BaCoO_2 composition point and the barium ferrite composition points belonging to opposite sides of the concentration triangle, except for the formation of bonds between BaCoO_2 and each of the barium ferrites ($\text{Ba}_2\text{Fe}_6\text{O}_{11}$, BaFe_2O_4 , $\text{Ba}_2\text{Fe}_2\text{O}_5$, $\text{Ba}_3\text{Fe}_2\text{O}_6$, $\text{Ba}_7\text{Fe}_4\text{O}_{13}$, and $\text{Ba}_5\text{Fe}_2\text{O}_8$). All established conjugates represent thermodynamically stable pair combinations of compounds in the system. Triple stable combinations of compounds are defined by composition points at the vertices of elementary triangles in a triangulated system (Figure 2).

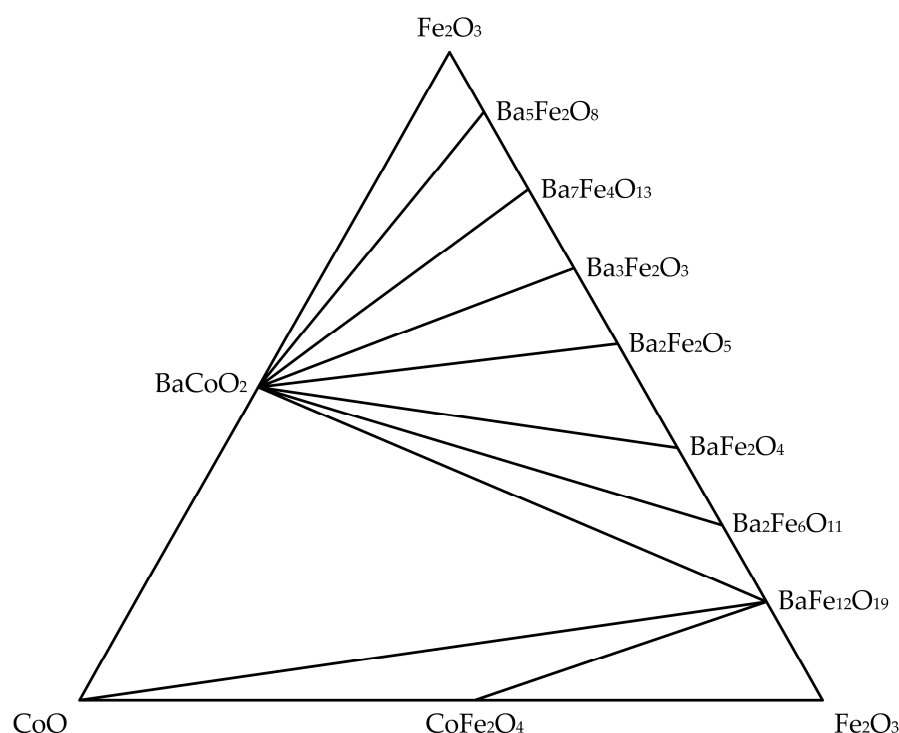


Figure 2. Subsolidus structure of the $\text{CoO--BaO--Fe}_2\text{O}_3$ system without considering ternary compounds.

For complete triangulation of the system under study, it was sufficient to analyze the results of calculations of ΔG values for four solid-phase reactions of the “2 = 2” type (Table 2) with the possibility of their coupling with the “3 = 2” type interaction mechanism. The entire array of compiled equations of reactions of the type “2 = 2” was not required, however, to confirm the connections between BaCoO_2 and barium ferrites; Table 2 presents reactions No. 5–8 involving CoO and barium ferrites. As follows from the negative values of ΔG for reactions No. 5–8, the $\text{BaCoO}_2\text{--BaFe}_{12}\text{O}_{19}$ compound is stable, and, accordingly, the $\text{BaCoO}_2\text{--Ba}_2\text{Fe}_6\text{O}_{11}$, $\text{BaCoO}_2\text{--BaFe}_2\text{O}_4$, $\text{BaCoO}_2\text{--Ba}_2\text{Fe}_2\text{O}_5$, $\text{BaCoO}_2\text{--Ba}_3\text{Fe}_2\text{O}_6$, $\text{BaCoO}_2\text{--Ba}_7\text{Fe}_4\text{O}_{13}$, and $\text{BaCoO}_2\text{--Ba}_5\text{Fe}_2\text{O}_8$ compounds are also stable and have no alternatives.

4. Conclusions

Based on the results of thermodynamic calculations of phase equilibria of exchange reactions in the subsolidus of the $\text{CoO--BaO--Fe}_2\text{O}_3$ system, ten stable ternary combinations of compounds were found, whose composition points correspond to the vertices of elementary triangles, as well as nine stable binary combinations of compounds, whose points define the ends of the edges in a triangulated system. Information about all variants

of thermodynamically equilibrium combinations of compounds forms the physicochemical basis for predicting the phase composition of materials during their synthesis in any concentration range of the system under study. The analysis revealed a certain predisposition to destabilization of the combination of compounds whose composition points are determined by the CoFe_2O_4 – $\text{BaFe}_{12}\text{O}_{19}$ line. The structural and phase stabilization of this compound is ensured by a complex mechanism of exchange interaction, which establishes an equilibrium three-phase combination within the concentration range of the elementary triangle CoFe_2O_4 – CoO – $\text{BaFe}_{12}\text{O}_{19}$. The results of the analysis of this situation are summarized in the form of a rule that allows establishing thermodynamic equilibrium combinations of compounds participating in solid-phase exchange reactions of the “3 = 2” type. The noted predisposition to destabilization of the CoFe_2O_4 – $\text{BaFe}_{12}\text{O}_{19}$ phase may be one of the reasons for the formation of a triple oxide compound, $\text{BaCo}_2\text{Fe}_{16}\text{O}_{27}$, whose composition point belongs to the specified phase. Changes in the subsolidus structure of the CoO – BaO – Fe_2O_3 system, taking into account triple oxide compounds, are to be established in further research. The inclusion of ternary ferrite phases may significantly modify the triangulation of the system and will be considered in future studies.

Author Contributions: Conceptualization: N.T., H.S. and E.H.; methodology: S.L. and N.T.; formal analysis: N.T. and H.S.; investigation: all authors; data curation: S.L. and V.N.; writing—original draft: N.T. and H.S.; writing—review and editing: A.G.M. and E.H.; supervision: A.G.M. and E.H.; project administration: E.H. All authors have read and agreed to the published version of the manuscript.

Funding: The study was conducted without financial support.

Data Availability Statement: Data available on request due to privacy restrictions.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Jabbar, R. Green synthesis of cobalt ferrite nanoparticles: From fundamentals to advanced applications. *Next Mater.* **2025**, *9*, 101327. [\[CrossRef\]](#)
2. Salih, S.J.; Mahmood, W.M. Review on magnetic spinel ferrite (MFe_2O_4) nanoparticles: From synthesis to application. *Heliyon* **2023**, *9*, e16601. [\[CrossRef\]](#) [\[PubMed\]](#)
3. Kumar, S.; Prakash, J.; Verma, A.; Jasrotia, R. A comprehensive review of synthesis, properties, and applications of $\text{BaFe}_{12}\text{O}_{19}$ hexaferrites. *Mater. Today Proc.* **2023**. [\[CrossRef\]](#)
4. Wagner, D.V.; Kareva, K.V.; Zhuravlev, V.A.; Dotsenko, O.A.; Minin, R.V. Investigation of $\text{BaFe}_{12}\text{O}_{19}$ hexaferrites manufactured by various synthesis methods using a developed pulsed magnetometer. *Inventions* **2023**, *8*, 26. [\[CrossRef\]](#)
5. Suganya, M.; Kishor Kumar, J.; Anand, S.; Mohamed Racik, K.; Muthupandi, S.; Muniyappan, S.; Nandhini, S. Synthesis and electrochemical investigation of Z-type barium hexaferrite nanoplatelets. *Inorg. Chem. Commun.* **2022**, *139*, 109412. [\[CrossRef\]](#)
6. Tang, J.; Liu, X.; Mahmood Ur Rehman, K.; Li, D.; Li, M.; Yang, Y. Microstructure and characterization of W-type hexaferrite $\text{Ba}_{1-x}\text{La}_x\text{Fe}_2^{2+}\text{Fe}_{16}^{3+}\text{O}_{27}$ prepared by solid state method. *J. Magn. Magn. Mater.* **2018**, *452*, 354–359. [\[CrossRef\]](#)
7. Chauhan, C.; Jotania, R.B. Structural and magnetic properties of $\text{BaCo}_{2-x}\text{Ni}_x\text{Fe}_{16}\text{O}_{27}$ hexagonal ferrite prepared by a simple heat treatment method. *Nanosyst. Phys. Chem. Math.* **2016**, *7*, 595–598. [\[CrossRef\]](#)
8. Li, J.; Yao, H.; Huang, Y.; Wang, H. Microwave absorption and magnetic properties of M-type hexagonal ferrite $\text{Ba}_{0.95}\text{Ca}_{0.05}\text{Fe}_{12-x}\text{Co}_x\text{O}_{19}$ ($0 \leq x \leq 0.4$) at 1–18 GHz. *Materials* **2024**, *17*, 5327. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Pullar, R.C. Magnetic properties of aligned Co_2Z hexagonal Z-ferrite fibers. *Int. J. Appl. Ceram. Technol.* **2014**, *11*, 451–456. [\[CrossRef\]](#)
10. Singh, V.P.; Jasrotia, R.; Kumar, R.; Raizada, P.; Thakur, S.; Batoo, K.M.; Singh, M. A current review on the synthesis and magnetic properties of M-type hexaferrites material. *World J. Condens. Matter Phys.* **2018**, *8*, 36–61. [\[CrossRef\]](#)

11. Logvinkov, S.M.; Borisenko, O.N.; Tsapko, N.S.; Shabanova, G.N.; Korohodska, A.N.; Shumejko, V.N.; Gaponova, O. Calculated evaluation of the degree of subsolidus structure complexity of the physico-chemical three-component systems. *Bull. Natl. Tech. Univ. KhPI. Ser. Chem. Chem. Technol. Ecol.* **2020**, *2*, 57–67. [[CrossRef](#)]
12. Shabanova, G.M. *Barium-Containing Oxide Systems and Binding Materials Based on Them*; NTU “KhPI”: Kharkiv, Ukraine, 2006; p. 280.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.