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### $(\phi, \rho)$ -Representation of $\Gamma$ -So-Rings

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ABSTRACT. A  $\Gamma$ -so-ring is a structure possessing a natural partial ordering, an infinitary partial addition and a ternary multiplication, subject to a set of axioms. The partial functions under disjoint-domain sums and functional composition is a  $\Gamma$ -so-ring. In this paper we introduce the notions of subdirect product and  $(\phi, \rho)$ -product of  $\Gamma$ -so-rings and study  $(\phi, \rho)$ -representation of  $\Gamma$ -so-rings.

**Keywords:** Subdirectly irreducible  $\Gamma$ -so-ring, Subdirect product,  $(\phi, \rho)$ -product of  $\Gamma_i$ -so-rings,  $(\phi, \rho)$ -representation of a  $\Gamma$ -so-ring.

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#### 1. INTRODUCTION

Partially defined infinitary operations occur in the contexts ranging from integration theory to programming language semantics. The general cardinal algebras studied by Tarski in 1949, Housdorff topological commutative groups studied by Bourbaki in 1966,  $\Sigma$ -structures studied by Higgs in 1980, sum ordered partial monoids & sum ordered partial semirings studied by Arbib,

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Manes, Benson[2],[3] and Streenstrup[6] are some of the algebraic structures of the above type.

M. Murali Krishna Rao[4] in 1995 introduced the notion of a  $\Gamma$ -semiring as a generalization of semirings and  $\Gamma$ -rings, and extended many fundamental results of semirings and  $\Gamma$ -rings to  $\Gamma$ -semirings. In [5] we introduced the notion of  $\Gamma$ -so-ring  $R$  and obtained a necessary and sufficient condition for the quotient  $R/\theta$  to be a  $\Gamma/\sigma$ -so-ring, where  $(\theta, \sigma)$  is a congruence relation on  $(R, \Gamma)$ . As a continuation, in this paper we prove that a  $\Gamma$ -so-ring is a subdirect product of subdirectly irreducible  $\Gamma_i$ -so-rings and obtain  $(\phi, \rho)$ -representation of  $\Gamma$ -so-rings.

## 2. PRELIMINARIES

In this section we collect important definitions from the literature.

**Definition 2.1**[3]. A *partial monoid* is a pair  $(M, \Sigma)$  where  $M$  is a nonempty set and  $\Sigma$  is a partial addition defined on some, but not necessarily all families  $(x_i : i \in I)$  in  $M$  subject to the following axioms:

- (1) **Unary Sum Axiom.** If  $(x_i : i \in I)$  is a one element family in  $M$  and  $I = \{j\}$ , then  $\Sigma(x_i : i \in I)$  is defined and equals  $x_j$ .
- (2) **Partition-Associativity Axiom.** If  $(x_i : i \in I)$  is a family in  $M$  and  $(I_j : j \in J)$  is a partition of  $I$ , then  $(x_i : i \in I)$  is summable if and only if  $(x_i : i \in I_j)$  is summable for every  $j$  in  $J$ ,  $(\Sigma(x_i : i \in I_j) : j \in J)$  is summable, and  $\Sigma(x_i : i \in I) = \Sigma(\Sigma(x_i : i \in I_j) : j \in J)$ .

**Example 2.2**[3]. Let  $D$  and  $E$  be two sets and let the set of all partial functions from  $D$  to  $E$  be denoted by  $Pfn(D, E)$ . A family  $(x_i : i \in I)$  is summable if and only if for  $i, j$  in  $I$ , and  $i \neq j$ ,  $dom(x_i) \cap dom(x_j) = \emptyset$ . If  $(x_i : i \in I)$  is summable then for any  $d$  in  $D$

$$d(\Sigma_i x_i) = \begin{cases} dx_i, & \text{if } d \in dom(x_i) \text{ for some (necessarily unique) } i \in I; \\ \text{undefined,} & \text{otherwise.} \end{cases}$$

Then  $(Pfn(D, E), \Sigma)$  is a partial monoid.

**Definition 2.3**[6]. Let  $(M, \Sigma)$  and  $(M', \Sigma')$  be partial monoids. Then  $(M', \Sigma')$  is said to be a *partial submonoid* of  $(M, \Sigma)$  if it satisfies the following:

- (1)  $M'$  is a subset of  $M$ ,
- (2)  $(x_i : i \in I)$  is a summable family in  $M'$  implies that  $(x_i : i \in I)$  is summable family in  $M$  and  $\Sigma'_i x_i = \Sigma_i x_i$ .

**Definition 2.4**[5]. Let  $(R, \Sigma)$  and  $(\Gamma, \Sigma')$  be two partial monoids. Then  $R$  is said to be a *partial  $\Gamma$ -semiring* if there exists a mapping  $R \times \Gamma \times R \rightarrow R$

(images to be denoted by  $x\gamma y$  for  $x, y \in R$  and  $\gamma \in \Gamma$ ) satisfying the following axioms:

- (1)  $x\gamma(y\mu z) = (x\gamma y)\mu z$ ,
- (2) a family  $(x_i : i \in I)$  is summable in  $R$  implies  $(x\gamma x_i : i \in I)$  is summable in  $R$  and  $x\gamma[\Sigma(x_i : i \in I)] = \Sigma(x\gamma x_i : i \in I)$ ,
- (3) a family  $(x_i : i \in I)$  is summable in  $R$  implies  $(x_i\gamma x : i \in I)$  is summable in  $R$  and  $[\Sigma(x_i : i \in I)]\gamma x = \Sigma(x_i\gamma x : i \in I)$ ,
- (4) a family  $(\gamma_i : i \in I)$  is summable in  $\Gamma$  implies  $(x\gamma_i y : i \in I)$  is summable in  $R$  and  $x[\Sigma'(\gamma_i : i \in I)]y = \Sigma(x\gamma_i y : i \in I)$  for all  $x, y, z, (x_i : i \in I)$  in  $R$  and  $\mu, \gamma, (\gamma_i : i \in I)$  in  $\Gamma$ .

**Definition 2.5**[5]. Let  $R$  be a partial  $\Gamma$ -semiring. Let  $A$  be a nonempty subset of  $R$  and  $\Gamma'$  be a nonempty subset of  $\Gamma$ . Then the pair  $(A, \Gamma')$  is said to be a *partial sub  $\Gamma$ -semiring* if

- (i)  $A$  is a partial submonoid of  $R$ ,
- (ii)  $\Gamma'$  is a partial submonoid of  $\Gamma$ ,
- (iii)  $A\Gamma'A \subseteq A$ .

**Definition 2.6**[6]. The *sum ordering*  $\leq$  on a partial monoid  $(M, \Sigma)$  is the binary relation such that  $x \leq y$  if and only if there exists an  $h$  in  $M$  such that  $y = x + h$  for  $x, y \in M$ .

**Definition 2.7**[6]. A *sum-ordered partial monoid* or *so-monoid*, in short, is a partial monoid in which the sum ordering is a partial ordering.

**Definition 2.8**[5]. A partial  $\Gamma$ -semiring  $R$  is said to be a *sum-ordered partial  $\Gamma$ -semiring* (in short  $\Gamma$ -so-ring) if the partial monoids  $R$  and  $\Gamma$  are so-monoids.

The *support* of a family  $(x_i : i \in I)$  in  $M$  is defined to be the subfamily  $(x_i : i \in J)$  where  $J = \{i \in I \mid x_i \neq 0\}$ .

**Example 2.9**[5] Let  $R = \Gamma := \mathbb{Z}^- \cup \{0\}$ , the set of all nonpositive integers. Then  $R$  and  $\Gamma$  are partial monoids with finite support addition. Now  $R$  is a partial  $\Gamma$ -semiring with usual multiplication of integers. Also  $R$  is a  $\Gamma$ -so-ring with the partial order “usual less than or equal to”. However  $R$  is not a so-ring in the sense of [9]. Since  $-2, -3 \in R$  and  $(-2)(-3) = 6 \notin R$ .

**Example 2.10**[5]. Let  $D, E$  be any two sets. Then  $Pfn(D, E)$  and  $Pfn(E, D)$  are partial monoids with the summations defined as in the Example 2.2. Consider the mapping  $(f, \gamma, g) \mapsto f\gamma g$  of  $Pfn(D, E) \times Pfn(E, D) \times Pfn(D, E)$  into  $Pfn(D, E)$  where  $d(f\gamma g) = (((df)\gamma)g)$ , for any  $d \in D$ . Then  $Pfn(D, E)$

is a partial  $Pfn(E, D)$ -semiring.

In general  $Pfn(D, E)$  is not  $Pfn(E, D)$ -semiring, since a family in the partial  $Pfn(E, D)$ -semiring  $Pfn(D, E)$  need not be summable.

**Example 2.11**[5]. Let  $R$  be the partial monoid of all  $m \times n$  matrices over the set of all non negative rational numbers and  $\Gamma$  be the partial monoid of all  $n \times m$  matrices over the set of all non negative integers. For any  $A, B \in R$  and  $\alpha \in \Gamma$ , consider the mapping  $(A, \alpha, B) \mapsto A\alpha B$ , usual matrix multiplication, of  $R \times \Gamma \times R$  into  $R$ . Then  $R$  is a partial  $\Gamma$ -semiring.

**Definition 2.12**[3]. Let  $(M, \Sigma)$ ,  $(M', \Sigma')$  be two partial monoids. Then a function  $\phi : M \rightarrow M'$  is said to be an *additive map* of  $(M, \Sigma)$  into  $(M', \Sigma')$  if  $(x_i : i \in I)$  is a summable family in  $M$  implies  $(x_i\phi : i \in I)$  is a summable family in  $M'$  and  $(\Sigma_i x_i)\phi = \Sigma'_i(x_i\phi)$ .

**Definition 2.13**[5]. Let  $R$  be a partial  $\Gamma$ -semiring and  $R'$  be a partial  $\Gamma'$ -semiring. Then a pair of mappings  $f : R \rightarrow R'$  and  $g : \Gamma \rightarrow \Gamma'$  is said to be a *homomorphism* from  $(R, \Gamma)$  into  $(R', \Gamma')$  if it satisfies the following:

- (i)  $f$  is an additive map from  $R$  into  $R'$ ,
- (ii)  $g$  is an additive map from  $\Gamma$  into  $\Gamma'$ , and
- (iii)  $f(a\gamma b) = f(a)g(\gamma)f(b)$  for any  $a, b \in R$  and  $\gamma \in \Gamma$ .

**Definition 2.14**[5]. Let  $R$  be a partial  $\Gamma$ -semiring,  $\theta$  be a binary relation on  $R$  and  $\sigma$  be a binary relation on  $\Gamma$ . Then the pair  $(\theta, \sigma)$  is called a *partial  $\Gamma$ -semiring congruence relation* on  $(R, \Gamma)$  if it satisfies the following:

- (i)  $\theta$  and  $\sigma$  are equivalence relations on  $R$  and  $\Gamma$  respectively,
- (ii)  $\theta$  ( $\sigma$ ) is closed under the additive operation of the product partial monoid  $R \times R$  ( $\Gamma \times \Gamma$ ). i.e., if  $(a_i : i \in I)$  and  $(b_i : i \in I)$  are summable families in  $R$  ( $\Gamma$ ) such that  $(a_i, b_i) \in \theta$  ( $\sigma$ ) for all  $i \in I$  then  $\Sigma_i(a_i, b_i) \in \theta$  ( $\Sigma'_i(a_i, b_i) \in \sigma$ ),
- (iii)  $(a, b) \in \theta$ ,  $(\alpha, \beta) \in \sigma$  and  $(c, d) \in \theta$  then  $(a\alpha c, b\beta d) \in \theta$ .

**Definition 2.15**[1]. A partial monoid congruence relation  $\theta$  on a partial monoid  $R$  is said to have the *diagonal property* if it satisfies the condition that for any  $a, b \in R$ ,  $a\theta(b+k)$  and  $(a+h)\theta b$  for some  $h, k \in R \Leftrightarrow a\theta b$ .

**Definition 2.16**[5]. Let  $R$  be a partial  $\Gamma$ -semiring. Then a partial  $\Gamma$ -semiring congruence relation  $(\theta, \sigma)$  on  $(R, \Gamma)$  is said to have the *diagonal property* if and only if  $\theta$  and  $\sigma$  have the diagonal property.

**Definition 2.17**[5]. A partial  $\Gamma$ -semiring congruence relation  $(\theta, \sigma)$  on a  $\Gamma$ -soring  $R$  is said to be a *congruence relation* on  $(R, \Gamma)$  if and only if  $(\theta, \sigma)$  has the

diagonal property.

**Definition 2.18**[5]. Let  $R$  be a partial  $\Gamma$ -semiring,  $\theta$  be a partial  $\Gamma$ -semiring  $\Gamma$ -congruence relation on  $R$ . Then  $\theta$  is said to be a  $\Gamma$ -congruence relation on  $R$  if and only if  $\theta$  has the diagonal property.

**Example 2.19.** Consider the  $\Gamma$ -so-ring  $R := Z^- \cup \{0\}$  as in the Example 2.9. Define  $\theta = \sigma$  on  $R$  as  $a\theta b$  if and only if  $a = b$ . Then  $(\theta, \sigma)$  is a partial  $\Gamma$ -semiring congruence relation on  $(R, \Gamma)$  such that  $(\theta, \sigma)$  satisfies the diagonal property. Therefore  $(\theta, \sigma)$  is a congruence relation on  $(R, \Gamma)$ . However  $\theta$  is not a partial semiring congruence relation on  $R$  as given in [7] and  $(\theta, \sigma)$  is not a congruence relation on  $(R, \Gamma)$  in the sense of [4]. Since  $R$  is not a so-ring as in [7] and  $\Gamma$ -semiring as in [4].

We denote the set of all congruence relations of a  $\Gamma$ -so-ring  $R$  by  $Con(R, \Gamma)$  and the set of all  $\Gamma$ -congruence relations of  $R$  by  $ConR$ .

### 3. STRUCTURE THEOREM

**Definition 3.1.** Let  $\{R_i \mid i \in I\}$  be a family of  $\Gamma_i$ -so-rings. Take  $R = \prod_{i \in I} R_i$  and  $\Gamma = \prod_{i \in I} \Gamma_i$ . Let  $R'$  and  $\Gamma'$  be subsets of  $R$  and  $\Gamma$  respectively. Then the pair  $(R', \Gamma')$  is said to be a *subdirect product* of  $(R_i, \Gamma_i)$ ,  $i \in I$  if it satisfies the following:

- (i)  $(R', \Gamma')$  is a sub  $\Gamma$ -so-ring of  $R$ ,
- (ii) all the projection mappings of  $(R, \Gamma)$  restricted to  $(R', \Gamma')$  are epimorphisms.

**Definition 3.2.** Let  $\{R_i \mid i \in I\}$  be a family of  $\Gamma$ -so-rings. Then a subset  $R$  of  $\prod_{i \in I} R_i$  is said to be a  $\Gamma$ -subdirect product of  $R_i$ ,  $i \in I$  if it satisfies the following:

- (i)  $R$  is a  $\Gamma$ -sub so-ring of  $\prod_{i \in I} R_i$ ,
- (ii) all the projection mappings of  $\prod_{i \in I} R_i$  restricted to  $R$  are epimorphisms.

**Definition 3.3.** A  $\Gamma$ -so-ring  $R$  is said to be *subdirectly irreducible* if and only if  $\bigcap_{i \in I} (\theta_i, \sigma_i) = (0_R, 0_\Gamma)$  where  $\{(\theta_i, \sigma_i) \mid i \in I\}$  is a family of congruence relations on  $(R, \Gamma)$  implies  $(\theta_i, \sigma_i) = (0_R, 0_\Gamma)$  for some  $i \in I$ .

**Definition 3.4.** A  $\Gamma$ -so-ring  $R$  is said to be  $\Gamma$ -subdirectly irreducible if and only if  $\bigcap_{i \in I} \theta_i = 0_R$  where  $\{\theta_i \mid i \in I\}$  is a family of  $\Gamma$ -congruence relations on  $R$

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implies  $\theta_i = 0_R$  for some  $i \in I$ .

**Lemma 3.5.** *Let  $R$  be a  $\Gamma$ -so-ring and  $(\theta, \sigma)$  be a congruence relation on  $(R, \Gamma)$ . Then there is a one to one correspondence between congruence relations on  $(R, \Gamma)$  containing  $(\theta, \sigma)$  and congruence relations on  $(R/\theta, \Gamma/\sigma)$ .*

*Proof.* Let  $(\phi, \rho)$  be a congruence relation on  $(R, \Gamma)$  containing  $(\theta, \sigma)$ . Define a relation  $\phi/\theta$  on  $R/\theta$  by  $[a]^\theta(\phi/\theta)[b]^\theta$  if and only if  $a\phi b$ , where  $[a]^\theta$  ( $[b]^\theta$ ) denotes the equivalence class containing  $a$  ( $b$ ) relative to  $\theta$  and define a relation  $\rho/\sigma$  on  $\Gamma/\sigma$  by  $[\alpha]^\sigma(\rho/\sigma)[\beta]^\sigma$  if and only if  $\alpha\rho\beta$ , where  $[\alpha]^\sigma$  ( $[\beta]^\sigma$ ) denotes the equivalence class containing  $\alpha$  ( $\beta$ ) relative to  $\sigma$ . Since  $(\phi, \rho)$  is an equivalence relation on  $(R, \Gamma)$ , it follows that  $(\phi/\theta, \rho/\sigma)$  is also an equivalence relation on  $(R/\theta, \Gamma/\sigma)$ . To prove  $(\phi/\theta, \rho/\sigma)$  is congruence, let  $([a_i]^\theta : i \in I)$  and  $([b_i]^\theta : i \in I)$  be summable families in  $R/\theta$  such that  $[a_i]^\theta(\phi/\theta)[b_i]^\theta, i \in I$ . Then  $(a_i : i \in I)$  and  $(b_i : i \in I)$  are summable families in  $R$  such that  $a_i\phi b_i, i \in I \Rightarrow (\sum_i a_i)\phi(\sum_i b_i) \Rightarrow [\sum_i a_i]^\theta(\phi/\theta)[\sum_i b_i]^\theta$  and hence  $\overline{\sum}_i [a_i]^\theta(\phi/\theta)\overline{\sum}_i [b_i]^\theta$ . Let  $([\alpha_i]^\sigma : i \in I)$  and  $([\beta_i]^\sigma : i \in I)$  be summable families in  $\Gamma/\sigma$  such that  $[\alpha_i]^\sigma(\rho/\sigma)[\beta_i]^\sigma, i \in I$ . Then  $(\alpha_i : i \in I)$  and  $(\beta_i : i \in I)$  are summable families in  $\Gamma$  such that  $\alpha_i\rho\beta_i, i \in I \Rightarrow (\sum_i \alpha_i)\rho(\sum_i \beta_i) \Rightarrow [\sum_i \alpha_i]^\sigma(\rho/\sigma)[\sum_i \beta_i]^\sigma$  and hence  $\overline{\sum}_i [\alpha_i]^\sigma(\rho/\sigma)\overline{\sum}_i [\beta_i]^\sigma$ . Let  $[a]^\theta(\phi/\theta)[b]^\theta, [\alpha]^\sigma(\rho/\sigma)[\beta]^\sigma$  and  $[c]^\theta(\phi/\theta)[d]^\theta$  where  $a, b, c, d \in R$  and  $\alpha, \beta \in \Gamma$ . Then  $a\phi b, \alpha\rho\beta$  and  $c\phi d \Rightarrow (a\alpha c)\phi(b\beta d)$  and hence  $([a]^\theta[\alpha]^\sigma[c]^\theta)(\phi/\theta)([b]^\theta[\beta]^\sigma[d]^\theta)$ . Hence  $(\phi/\theta, \rho/\sigma)$  is a partial  $\Gamma/\sigma$ -semiring congruence relation on  $R/\theta$ . Note that  $[a]^\theta(\phi/\theta)([b]^\theta + [h]^\theta)$  and  $([a]^\theta + [k]^\theta)(\phi/\theta)[b]^\theta$  for some  $h, k \in R \Leftrightarrow a\phi(b+h)$  and  $(a+k)\phi b \Leftrightarrow a\phi b \Leftrightarrow [a]^\theta(\phi/\theta)[b]^\theta$ . Therefore  $\phi/\theta$  has the diagonal property. Also note that  $[\alpha]^\sigma(\rho/\sigma)([\beta]^\sigma + [h]^\sigma)$  and  $([\alpha]^\sigma + [k]^\sigma)(\rho/\sigma)[\beta]^\sigma$  for some  $h, k \in \Gamma \Leftrightarrow \alpha\rho(\beta+h)$  and  $(\alpha+k)\rho\beta \Leftrightarrow \alpha\rho\beta \Leftrightarrow [\alpha]^\sigma(\rho/\sigma)[\beta]^\sigma$ . Therefore  $\rho/\sigma$  has the diagonal property. Hence  $(\phi/\theta, \rho/\sigma)$  is a congruence relation on  $(R/\theta, \Gamma/\sigma)$ .

Let  $(\phi', \rho')$  be a congruence relation on  $(R/\theta, \Gamma/\sigma)$ . Define a relation  $\phi_\theta$  on  $R$  by  $a\phi_\theta b$  if and only if  $[a]^\theta\phi'[b]^\theta$  and a relation  $\rho_\sigma$  on  $\Gamma$  by  $\alpha\rho_\sigma\beta$  if and only if  $[\alpha]^\sigma\rho'[\beta]^\sigma$ . Since  $(\phi', \rho')$  is an equivalence relation on  $(R/\theta, \Gamma/\sigma)$ , it follows that  $(\phi_\theta, \rho_\sigma)$  is also an equivalence relation on  $(R, \Gamma)$ . To prove  $(\phi', \rho')$  is congruence, let  $(a_i : i \in I)$  and  $(b_i : i \in I)$  be summable families in  $R$  such that  $a_i\phi_\theta b_i, i \in I$ . Then  $([a_i]^\theta : i \in I)$  and  $([b_i]^\theta : i \in I)$  are summable families in  $R/\theta$  such that  $[a_i]^\theta\phi'[b_i]^\theta, i \in I \Rightarrow \overline{\sum}_i [a_i]^\theta\phi'\overline{\sum}_i [b_i]^\theta$  and hence  $(\sum_i a_i)\phi_\theta(\sum_i b_i)$ . Let  $(\alpha_i : i \in I)$  and  $(\beta_i : i \in I)$  be summable families in  $\Gamma$  such that  $\alpha_i\rho_\sigma\beta_i, i \in I$ . Then  $([\alpha_i]^\sigma : i \in I)$  and  $([\beta_i]^\sigma : i \in I)$  are summable families in  $\Gamma/\sigma$  such that  $[\alpha_i]^\sigma\rho'[\beta_i]^\sigma, i \in I \Rightarrow \overline{\sum}_i [\alpha_i]^\sigma\rho'\overline{\sum}_i [\beta_i]^\sigma$  and hence  $(\sum_i \alpha_i)\rho_\sigma(\sum_i \beta_i)$ . Let  $a\phi_\theta b, \alpha\rho_\sigma\beta$  and  $c\phi_\theta d$  where  $a, b, c, d \in R$  and  $\alpha, \beta \in \Gamma$ . Then  $[a]^\theta\phi'[b]^\theta, [\alpha]^\sigma\rho'[\beta]^\sigma$  and  $[c]^\theta\phi'[d]^\theta \Rightarrow [a\alpha c]^\theta\phi'[b\beta d]^\theta$  and hence  $(a\alpha c)\phi_\theta(b\beta d)$ . Hence  $(\phi_\theta, \rho_\sigma)$  is a partial  $\Gamma$ -semiring congruence relation on  $R$ . Note that  $a\phi_\theta(b+h)$  and  $(a+k)\phi_\theta b$  for some  $h, k \in R \Leftrightarrow [a]^\theta\phi'([b]^\theta + [h]^\theta)$  and

$([a]^\theta + [k]^\theta)\phi'[b]^\theta \Leftrightarrow [a]^\theta\phi'[b]^\theta \Leftrightarrow a\phi_\theta b$ . Therefore  $\phi_\theta$  has the diagonal property. Also note that  $\alpha\rho_\sigma(\beta+h)$  and  $(\alpha+k)\rho_\sigma\beta$  for some  $h, k \in \Gamma \Leftrightarrow [\alpha]^\sigma\rho'([\beta]^\sigma + [h]^\sigma)$  and  $([\alpha]^\sigma + [k]^\sigma)\rho'[\beta]^\sigma \Leftrightarrow [\alpha]^\sigma\rho'[\beta]^\sigma \Leftrightarrow \alpha\rho_\sigma\beta$ . Therefore  $\rho_\sigma$  has the diagonal property. Let  $a\theta b$ . Then  $[a]^\theta = [b]^\theta \Rightarrow [a]^\theta\phi'[b]^\theta \Rightarrow a\phi_\theta b$ . Therefore  $\theta \subseteq \phi_\theta$ . Let  $\alpha\sigma\beta$ . Then  $[\alpha]^\sigma = [\beta]^\sigma \Rightarrow [\alpha]^\sigma\rho'[\beta]^\sigma \Rightarrow \alpha\rho_\sigma\beta$ . Therefore  $\sigma \subseteq \rho_\sigma$ . Hence  $(\phi_\theta, \rho_\sigma)$  is a congruence relation of  $(R, \Gamma)$  containing  $(\theta, \sigma)$ . The above definitions readily gives the correspondence. Hence the lemma.  $\square$

**Corollary 3.6.** *Let  $R$  be a  $\Gamma$ -so-ring and  $\theta$  be a  $\Gamma$ -congruence relation on  $R$ . Then there is a one to one correspondence between  $\Gamma$ -congruence relations on  $R$  containing  $\theta$  and  $\Gamma$ -congruence relations on  $R/\theta$ .*

**Lemma 3.7.** *Let  $R$  be a  $\Gamma$ -so-ring and  $\{(\theta_i, \sigma_i) \mid i \in I\}$  be a family of congruence relations on  $(R, \Gamma)$  such that  $\bigcap_{i \in I} (\theta_i, \sigma_i) = (0_R, 0_\Gamma)$ . Then  $(R, \Gamma)$  is isomorphic to a subdirect product of  $(R/\theta_i, \Gamma/\sigma_i)$ ,  $i \in I$ .*

*Proof.* Define  $f : R \rightarrow \prod_{i \in I} R/\theta_i$  by  $f(a) = ([a]^{\theta_i} : i \in I) \forall a \in R$  and  $g : \Gamma \rightarrow \prod_{i \in I} \Gamma/\sigma_i$  by  $g(\alpha) = ([\alpha]^{\sigma_i} : i \in I) \forall \alpha \in \Gamma$ . First we prove that  $(f, g)$

is a monomorphism. Let  $(x_j : j \in J)$  be a summable family in  $R$ . Then  $f(\sum_j x_j) = ([\sum_j x_j]^{\theta_i} : i \in I) = (\overline{\sum_j} [x_j]^{\theta_i} : i \in I) = \overline{\sum_j} f(x_j)$ . Let  $(\alpha_j : j \in J)$  be a summable family in  $\Gamma$ . Then  $g(\sum_j \alpha_j) = ([\sum_j \alpha_j]^{\sigma_i} : i \in I) = (\overline{\sum_j} [\alpha_j]^{\sigma_i} : i \in I) = \overline{\sum_j} g(\alpha_j)$ . For any  $x, y \in R$  and  $\alpha \in \Gamma$ ,  $f(x\alpha y) = ([x\alpha y]^{\theta_i} : i \in I) = ([x]^{\theta_i} [\alpha]^{\sigma_i} [y]^{\theta_i} : i \in I) = f(x)g(\alpha)f(y)$ . Let  $x, y \in R$  such that  $f(x) = f(y)$ . Then  $([x]^{\theta_i} : i \in I) = ([y]^{\theta_i} : i \in I) \Rightarrow [x]^{\theta_i} = [y]^{\theta_i} \forall i \in I \Rightarrow x(\bigcap_{i \in I} \theta_i)y \Rightarrow x = y$ . Let  $\alpha, \beta \in \Gamma$  such that  $g(\alpha) = g(\beta)$ . Then  $([\alpha]^{\sigma_i} : i \in I) = ([\beta]^{\sigma_i} : i \in I) \Rightarrow [\alpha]^{\sigma_i} = [\beta]^{\sigma_i} \forall i \in I \Rightarrow \alpha(\bigcap_{i \in I} \sigma_i)\beta \Rightarrow \alpha = \beta$ . Hence  $(f, g)$  is

a monomorphism from  $(R, \Gamma)$  into  $\prod_{i \in I} (R/\theta_i, \Gamma/\sigma_i)$ . Consequently  $(f, g)$  is an isomorphism from  $(R, \Gamma)$  onto  $(f(R), g(\Gamma))$ .

Now we prove that  $(f(R), g(\Gamma))$  is a subdirect product of  $(R/\theta_i, \Gamma/\sigma_i)$ ,  $i \in I$ . It can be noted that  $(f(R), g(\Gamma))$  is a sub  $\prod_{i \in I} \Gamma/\sigma_i$ -so-ring of  $\prod_{i \in I} R/\theta_i$ . For any  $i \in I$ ,  $p_i(f(R)) = \{p_i(f(x)) \mid x \in R\} = \{p_i([x]^{\theta_i} : i \in I) \mid x \in R\} = \{[x]^{\theta_i} \mid x \in R\} = R/\theta_i$  and  $p'_i(g(\Gamma)) = \{p'_i(g(\alpha)) \mid \alpha \in \Gamma\} = \{p'_i([\alpha]^{\sigma_i} : i \in I) \mid \alpha \in \Gamma\} = \{[\alpha]^{\sigma_i} \mid \alpha \in \Gamma\} = \Gamma/\sigma_i$ . Hence  $(f(R), g(\Gamma))$  is a subdirect product of  $(R/\theta_i, \Gamma/\sigma_i)$ ,  $i \in I$ . Hence the lemma.  $\square$

**Corollary 3.8.** Let  $\{\theta_i \mid i \in I\}$  be a family of  $\Gamma$ -congruence relations on a  $\Gamma$ -so-ring  $R$  such that  $\bigcap_{i \in I} \theta_i = 0_R$ . Then  $R$  is isomorphic to a  $\Gamma$ -subdirect product of  $R/\theta_i$ ,  $i \in I$ .

**Lemma 3.9.** Let  $R$  be a  $\Gamma$ -so-ring and  $\{(\theta_i, \sigma_i) \mid i \in I\}$  be a simply ordered family of congruence relations on  $(R, \Gamma)$ . Then  $\bigvee_{i \in I} (\theta_i, \sigma_i) = \bigcup_{i \in I} (\theta_i, \sigma_i)$ .

*Proof.* Since the family  $\{(\theta_i, \sigma_i) \mid i \in I\}$  is simply ordered, it is obvious.  $\square$

**Corollary 3.10.** Let  $\{\theta_i \mid i \in I\}$  be a simply ordered family of  $\Gamma$ -congruence relations on a  $\Gamma$ -so-ring  $R$ . Then  $\bigvee_{i \in I} \theta_i = \bigcup_{i \in I} \theta_i$ .

**Lemma 3.11.** Let  $R$  be a  $\Gamma$ -so-ring. If  $a, b \in R$  with  $a \neq b$  and  $\alpha, \beta \in \Gamma$  with  $\alpha \neq \beta$ , then there is a congruence relation  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$  on  $(R, \Gamma)$  such that  $(a, b) \notin \theta_{(a,b)}$ ,  $(\alpha, \beta) \notin \sigma_{(\alpha,\beta)}$  and  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$  is maximal with respect to this property.

*Proof.* For any  $a, b \in R$  such that  $a \neq b$  and  $\alpha, \beta \in \Gamma$  such that  $\alpha \neq \beta$ , let  $\mathcal{C} = \{(\phi, \rho) \in \text{Con}(R, \Gamma) \mid (a, b) \notin \phi, (\alpha, \beta) \notin \rho\}$ . It is obvious that  $(0_R, 0_\Gamma) \in \mathcal{C}$ . So,  $\mathcal{C}$  is nonempty. By Zorn's lemma,  $\mathcal{C}$  has a maximal element, say  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ . Hence the lemma.  $\square$

**Corollary 3.12.** Let  $R$  be a  $\Gamma$ -so-ring. If  $a, b \in R$  with  $a \neq b$ , then there is a  $\Gamma$ -congruence relation  $\theta_{(a,b)}$  on  $R$  such that  $(a, b) \notin \theta_{(a,b)}$  and  $\theta_{(a,b)}$  is maximal with respect to this property.

**Lemma 3.13.** Let  $R$  be a  $\Gamma$ -so-ring. Then  $R$  is subdirectly irreducible if and only if  $\text{Con}(R, \Gamma)$  has one and only one atom which is contained in every congruence relation other than  $(0_R, 0_\Gamma)$ , the zero congruence relation on  $(R, \Gamma)$ .

*Proof.* It can be proved easily.  $\square$

**Corollary 3.14.** Let  $R$  be a  $\Gamma$ -so-ring. Then  $R$  is  $\Gamma$ -subdirectly irreducible if and only if  $\text{Con}R$  has one and only one atom which is contained in every  $\Gamma$ -congruence relation other than  $0_R$ , the zero  $\Gamma$ -congruence relation on  $R$ .

**Theorem 3.15.** A  $\Gamma$ -so-ring  $R$ , where both  $R$  and  $\Gamma$  are nonzero, is a subdirect product of subdirectly irreducible  $\Gamma_i$ -so-rings  $R_i$ ,  $i \in I$ .

*Proof.* Let  $R$  be a  $\Gamma$ -so-ring. Consider the family of congruences  $\mathcal{C} = \{(\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) \mid a, b \in R, \alpha, \beta \in \Gamma \text{ with } a \neq b \text{ and } \alpha \neq \beta\}$  as constructed in the Lemma 3.11. Suppose  $(x, y) \in \bigcap_{a \neq b} \theta_{(a,b)}$  and  $(\gamma, \mu) \in \bigcap_{\alpha \neq \beta} \sigma_{(\alpha,\beta)}$ . Then  $(x, y) \in \theta_{(a,b)} \forall a \neq b$  and  $(\gamma, \mu) \in \sigma_{(\alpha,\beta)} \forall \alpha \neq \beta$ . If  $x \neq y$  and  $\gamma \neq \mu$ , then  $(x, y) \in \theta_{(x,y)}$  and  $(\gamma, \mu) \in \sigma_{(\gamma,\mu)}$ , a contradiction. Hence  $(\bigcap_{a \neq b} \theta_{(a,b)}, \bigcap_{\alpha \neq \beta} \sigma_{(\alpha,\beta)}) = (0_R, 0_\Gamma)$ . By the Lemma 3.7,  $(R, \Gamma)$  is isomorphic to a subdirect product of  $\Gamma/\sigma_{(\alpha,\beta)}$ -so-rings  $R/\theta_{(a,b)}, a \neq b, \alpha \neq \beta$ .

Now we prove that  $R/\theta_{(a,b)}, a \neq b$  is a subdirectly irreducible  $\Gamma/\sigma_{(\alpha,\beta)}$ -so-ring,  $\alpha \neq \beta$ . Let  $([\theta_{(a,b)}], [\sigma_{(\alpha,\beta)}])$  denote the set of all congruence relations on  $(R, \Gamma)$  containing  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ . Let  $(\psi, \rho)$  be the smallest congruence relation such that  $(a, b) \in \psi$  and  $(\alpha, \beta) \in \rho$ . Then  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) \subseteq (\psi, \rho) \vee (\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ . If  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) = (\psi, \rho) \vee (\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ , then  $(\psi, \rho) \subseteq (\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ , and so  $(a, b) \in \theta_{(a,b)}$  for  $a \neq b$  and  $(\alpha, \beta) \in \sigma_{(\alpha,\beta)}$  for  $\alpha \neq \beta$ , a contradiction. Hence  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) \subset (\psi, \rho) \vee (\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) \Rightarrow (\psi, \rho) \vee (\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) \in ([\theta_{(a,b)}], [\sigma_{(\alpha,\beta)}])$  and  $(\psi, \rho) \vee (\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) \neq (\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ . Let  $(\phi, \tau)$  be another congruence relation in  $([\theta_{(a,b)}], [\sigma_{(\alpha,\beta)}])$  other than  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ . Then  $(a, b) \in \phi$  and  $(\alpha, \beta) \in \tau \Rightarrow (\psi, \rho) \subseteq (\phi, \tau)$ . Hence  $(\psi, \rho) \vee (\theta_{(a,b)}, \sigma_{(\alpha,\beta)}) \subseteq (\phi, \tau)$ . Therefore  $(\psi, \rho) \vee (\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$  is the only atom which is contained in every congruence relation in  $([\theta_{(a,b)}], [\sigma_{(\alpha,\beta)}])$  other than  $(\theta_{(a,b)}, \sigma_{(\alpha,\beta)})$ . By the Lemma 3.5, there is a one to one correspondence between the congruence relations on  $(R/\theta_{(a,b)}, \Gamma/\sigma_{(\alpha,\beta)})$ ,  $a \neq b, \alpha \neq \beta$  and  $([\theta_{(a,b)}], [\sigma_{(\alpha,\beta)}]) \Rightarrow \text{Con}(R/\theta_{(a,b)}, \Gamma/\sigma_{(\alpha,\beta)})$  has one and only one atom which is contained in every congruence relation other than  $(\overline{(\theta_{(a,b)}, \sigma_{(\alpha,\beta)})})$  (the zero congruence on  $(R/\theta_{(a,b)}, \Gamma/\sigma_{(\alpha,\beta)})$ ). By the Lemma 3.13,  $R/\theta_{(a,b)}, a \neq b$  is a subdirectly irreducible  $\Gamma/\sigma_{(\alpha,\beta)}$ -so-ring,  $\alpha \neq \beta$ . Hence the theorem.  $\square$

**Corollary 3.16.** *A  $\Gamma$ -so-ring  $R$ , where  $R$  is nonzero, is a  $\Gamma$ -subdirect product of  $\Gamma$ -subdirectly irreducible  $\Gamma$ -so-rings  $R_i, i \in I$ .*

#### 4. $(\phi, \rho)$ -REPRESENTATION OF $\Gamma$ -SO-RINGS

Walendziak[9] introduced the notion of  $\phi$ -representation of algebras and studied the necessary and sufficient condition for  $\langle (A_i : i \in I), f \rangle$  to be a  $\phi$ -representation. We extend these to  $\Gamma$ -so-rings.

**Definition 4.1.** Let  $\{R_i \mid i \in I\}$  be a family of  $\Gamma_i$ -so-rings,  $(R, \Gamma)$  be a subdirect product of  $(R_i, \Gamma_i), i \in I$ , and let  $(\phi, \rho) \in \text{Con}(R, \Gamma)$ . Then the pair  $(R, \Gamma)$  is said to be a  $(\phi, \rho)$ -product of  $(R_i, \Gamma_i), i \in I$  if it satisfies the following:

- (i) for every  $\bar{x} = (x_i : i \in I) \in R^I$ , if  $(x_i, x_j) \in \phi \forall i, j \in I$  then  $\langle x_i(i) : i \in I \rangle \in R$ ,

(ii) for every  $\bar{\alpha} = (\alpha_i : i \in I) \in \Gamma^I$ , if  $(\alpha_i, \alpha_j) \in \rho \forall i, j \in I$  then  $\langle \alpha_i(i) : i \in I \rangle \in \Gamma$ .

**Definition 4.2.** Let  $\{R_i \mid i \in I\}$  be a family of  $\Gamma$ -so-rings,  $R$  be a  $\Gamma$ -subdirect product of  $R_i, i \in I$ , and let  $\phi \in \text{Con}R$ . Then  $R$  is said to be a  $\phi$ -product of  $R_i, i \in I$  if it satisfies the condition that for every  $\bar{x} = (x_i : i \in I) \in R^I$ , if  $(x_i, x_j) \in \phi \forall i, j \in I$  then  $\langle x_i(i) : i \in I \rangle \in R$ .

**Example 4.3.** Take  $R_1 = \{0, 1\}$ . Define  $\Sigma$  on  $R_1$  as

$$\Sigma_i x_i = \begin{cases} 1, & \text{if } x_i = 0 \forall i \neq j \text{ for some } j \\ 1, & \text{if } x_h = 1, x_k = 1 \text{ for some } h, k, x_i = 0 \forall i \neq h, k \\ \text{undefined,} & \text{otherwise.} \end{cases}$$

Take  $\Gamma_1 = \{0', 1'\}$ . Define  $\Sigma'$  on  $\Gamma_1$  as

$$\Sigma'_i \alpha_i = \begin{cases} 1', & \text{if } \alpha_i = 0 \forall i \neq j \text{ for some } j \\ \text{undefined,} & \text{otherwise.} \end{cases}$$

Then  $R_1$  and  $\Gamma_1$  are partial monoids. Consider the mapping  $(x, \alpha, y) \mapsto x\alpha y$  of  $R_1 \times \Gamma_1 \times R_1$  into  $R_1$  as follows:

0'	0	1
0	0	0
1	0	0

1'	0	1
0	0	0
1	0	1

Then  $R_1$  is a  $\Gamma_1$ -so-ring. Take  $R_2 = \{0, a, 1\}$ . Define  $\Sigma$  on  $R_2$  as

$$\Sigma_i x_i = \begin{cases} x_j, & \text{if } x_i = 0 \forall i \neq j \text{ for some } j \\ a, & \text{if } x_h = x_k = a \text{ for some } h, k, x_i = 0 \forall i \neq h, k \\ 1, & \text{if } x_h = 1, x_k = a \text{ or } 1, \text{ for some } h, k, x_i = 0 \forall i \neq h, k \\ \text{undefined,} & \text{otherwise.} \end{cases}$$

Then  $R_2$  is a partial monoid. Take  $\Gamma_2 := \Gamma_1$ . Consider the mapping  $(x, \alpha, y) \mapsto x\alpha y$  of  $R_2 \times \Gamma_2 \times R_2$  into  $R_2$  as follows:

0'	0	a	1
0	0	0	0
a	0	0	0
1	0	0	0

1'	0	a	1
0	0	0	0
a	0	a	a
1	0	a	1

Then  $R_2$  is a  $\Gamma_2$ -so-ring. Also  $R_1 \times R_2$  is a  $\Gamma_1 \times \Gamma_2$ -so-ring. Take  $R = \{ \langle 0, 0 \rangle, \langle 1, 0 \rangle, \langle 1, a \rangle, \langle 1, 1 \rangle \}$ ,  $\Gamma = \{ \langle 0', 0' \rangle, \langle 1', 1' \rangle \}$ ,  $\theta = \{ (\langle 0, 0 \rangle, \langle 0, 0 \rangle), (\langle 1, 0 \rangle, \langle 1, 0 \rangle), (\langle 1, a \rangle, \langle 1, a \rangle), (\langle 1, 1 \rangle, \langle 1, 1 \rangle), (\langle 0, 0 \rangle, \langle 1, 0 \rangle), (\langle 1, 0 \rangle, \langle 0, 0 \rangle) \}$  and  $\rho = \{ (\langle 0', 0' \rangle, \langle 0', 0' \rangle), (\langle 1', 1' \rangle, \langle 1', 1' \rangle) \}$ . Then  $(R, \Gamma)$  is a subdirect product of  $(R_i, \Gamma_i), i = 1, 2$

and  $(\theta, \rho)$  is a congruence relation on  $(R, \Gamma)$ . Now for every  $\bar{x} = (x_1, x_2) \in R^2$ , if  $(x_1, x_1), (x_1, x_2), (x_2, x_1), (x_2, x_2) \in \theta$  then  $\langle x_1(1), x_2(2) \rangle \in R$  and  $\bar{\alpha} = (\alpha_1, \alpha_2) \in \Gamma^2$ , if  $(\alpha_1, \alpha_1), (\alpha_1, \alpha_2), (\alpha_2, \alpha_1), (\alpha_2, \alpha_2) \in \rho$  then  $\langle \alpha_1(1), \alpha_2(2) \rangle \in \Gamma$ . Also  $p_1(R) = R_1, p_2(R) = R_2$  and  $p'_1(\Gamma) = \Gamma_1, p'_2(\Gamma) = \Gamma_2$ . Hence  $(R, \Gamma)$  is a  $(\theta, \rho)$ -product of  $(R_i, \Gamma_i), i = 1, 2$ .

Now take  $\phi = \{(\langle 0, 0 \rangle, \langle 0, 0 \rangle), (\langle 1, 0 \rangle, \langle 1, 0 \rangle), (\langle 1, a \rangle, \langle 1, a \rangle), (\langle 1, 1 \rangle, \langle 1, 1 \rangle), (\langle 0, 0 \rangle, \langle 1, 0 \rangle), (\langle 1, 0 \rangle, \langle 0, 0 \rangle), (\langle 0, 0 \rangle, \langle 1, a \rangle), (\langle 1, a \rangle, \langle 0, 0 \rangle), (\langle 1, 0 \rangle, \langle 1, a \rangle), (\langle 1, a \rangle, \langle 1, 0 \rangle)\}$ . Then  $(\phi, \rho)$  is a congruence relation on  $(R, \Gamma)$ . Take  $\bar{x} = (\langle 0, 0 \rangle, \langle 1, a \rangle) \in R^2$ . Then  $(\langle 0, 0 \rangle, \langle 0, 0 \rangle), (\langle 0, 0 \rangle, \langle 1, a \rangle), (\langle 1, a \rangle, \langle 0, 0 \rangle), (\langle 1, a \rangle, \langle 1, a \rangle) \in \phi$ . But  $\langle \langle 0, 0 \rangle(1), \langle 1, a \rangle(2) \rangle = \langle 0, a \rangle \notin R$ . Thus  $(R, \Gamma)$  is not a  $(\phi, \rho)$ -product of  $(R_i, \Gamma_i), i = 1, 2$ .

**Lemma 4.4.** *Let  $R$  be a  $\Gamma$ -so-ring and  $R_i (i \in I)$  be a family of  $\Gamma_i$ -so-rings. Then*

(i)  *$(R, \Gamma)$  is a subdirect product of  $(R_i, \Gamma_i), i \in I$  if and only if  $(R, \Gamma)$  is a  $(0_R, 0_\Gamma)$ -product of  $(R_i, \Gamma_i), i \in I$ .*

(ii)  *$(R, \Gamma)$  is a  $(1_R, 1_\Gamma)$ -product of  $(R_i, \Gamma_i), i \in I$  if and only if  $(R, \Gamma) = \prod_{i \in I} (R_i, \Gamma_i)$ .*

*Proof.* (i) Suppose  $(R, \Gamma)$  is a  $(0_R, 0_\Gamma)$ -product of  $(R_i, \Gamma_i), i \in I$ . Then  $(R, \Gamma)$  is a subdirect product of  $(R_i, \Gamma_i), i \in I$ . Conversely, suppose that  $(R, \Gamma)$  is a subdirect product of  $\Gamma_i$ -so-rings  $R_i, i \in I$ . Let  $\bar{x} := (x_i : i \in I) \in R^I \ni (x_i, x_j) \in 0_R \forall i, j \in I$ . Then  $\langle x_i(i) : i \in I \rangle = x_i \in R$  (since  $x_i = x_j, \forall i, j \in I$ ). Let  $\bar{\alpha} := (\alpha_i : i \in I) \in \Gamma^I \ni (\alpha_i, \alpha_j) \in 0_\Gamma \forall i, j \in I$ . Then  $\langle \alpha_i(i) : i \in I \rangle = \alpha_i \in \Gamma$  (since  $\alpha_i = \alpha_j, \forall i, j \in I$ ). Hence  $(R, \Gamma)$  is a  $(0_R, 0_\Gamma)$ -product of  $(R_i, \Gamma_i), i \in I$ .

(ii) Suppose  $(R, \Gamma)$  is a  $(1_R, 1_\Gamma)$ -product of  $(R_i, \Gamma_i), i \in I$ . Let  $x \in \prod_{i \in I} R_i$ . Then  $x = \langle x_i : i \in I \rangle \in \prod_{i \in I} R_i$  where  $x_i \in R_i \forall i \in I$ . Since  $p_i|_R : R \rightarrow R_i$  is a surjective homomorphism,  $\exists a_i \in R \ni p_i|_R(a_i) = x_i \forall i \in I. \Rightarrow a_i(i) = x_i \forall i \in I$ . Put  $\bar{a} := (a_i : i \in I)$ . Since  $1_R = R^2, (a_i, a_j) \in 1_R \forall i, j \in I. \Rightarrow \langle a_i(i) : i \in I \rangle \in R. \Rightarrow x = \langle x_i : i \in I \rangle \in R$ . Hence  $R = \prod_{i \in I} R_i$ . Similarly,

we can prove that  $\Gamma = \prod_{i \in I} \Gamma_i$ .

Conversely suppose that  $(R, \Gamma) = \prod_{i \in I} (R_i, \Gamma_i)$ . Then  $(R, \Gamma)$  is clearly a subdirect product of  $(R_i, \Gamma_i), i \in I$ . Let  $\bar{x} := (x_i : i \in I) \in R^I \ni (x_i, x_j) \in 1_R \forall i, j \in I. \Rightarrow \langle x_i(i) : i \in I \rangle \in \prod_{i \in I} R_i = R$ . Let  $\bar{\alpha} := (\alpha_i : i \in I) \in \Gamma^I \ni$

$(\alpha_i, \alpha_j) \in 1_\Gamma \forall i, j \in I \Rightarrow \langle \alpha_i(i) : i \in I \rangle \in \prod_{i \in I} \Gamma_i = \Gamma$ . Hence  $(R, \Gamma)$  is a  $(1_R, 1_\Gamma)$ -product of  $(R_i, \Gamma_i), i \in I$ . □

**Corollary 4.5.** *Let  $R$  and  $R_i(i \in I)$  be a family of  $\Gamma$ -so-rings. Then*

(i)  *$R$  is a  $\Gamma$ -subdirect product of  $R_i, i \in I$  if and only if  $R$  is a  $0_R$ -product of  $R_i, i \in I$ .*

(ii)  *$R$  is a  $1_R$ -product of  $R_i, i \in I$  if and only if  $R = \prod_{i \in I} R_i$ .*

**Theorem 4.6.** *Let  $\{R_i \mid i \in I\}$  be a family of  $\Gamma_i$ -so-rings, let  $(R, \Gamma)$  be a sub  $\prod_{i \in I} \Gamma_i$ -ring of  $\prod_{i \in I} R_i$  and let  $(\phi, \rho) \in \text{Con}(R, \Gamma)$ . For  $i \in I$ , let  $\theta_i$  be the kernel of the projection at  $i$ , restricted to  $R$  and  $\sigma_i$  be the kernel of the projection at  $i$ , restricted to  $\Gamma$ . If  $(R, \Gamma)$  is a  $(\phi, \rho)$ -product of  $(R_i, \Gamma_i), i \in I$ , then*

(i)  $(0_R, 0_\Gamma) = \bigcap_{i \in I} (\theta_i, \sigma_i)$ ,

(ii) *for every  $\bar{x} = (x_i : i \in I) \in R^I$ , if  $(x_i, x_j) \in \phi \forall i, j \in I$ , then  $\exists x \in R \ni (x, x_i) \in \theta_i, \forall i \in I$ ,*

(iii) *for every  $\bar{\alpha} = (\alpha_i : i \in I) \in \Gamma^I$ , if  $(\alpha_i, \alpha_j) \in \rho \forall i, j \in I$ , then  $\exists \alpha \in \Gamma \ni (\alpha, \alpha_i) \in \sigma_i, \forall i \in I$ ,*

(iv)  $(R/\theta_i, \Gamma/\sigma_i) \cong (R_i, \Gamma_i) \forall i \in I$ .

*Proof.* (i) Let  $(x, y) \in \bigcap_{i \in I} \theta_i$  where  $x, y \in R$ . Then  $p_i|_R(x) = p_i|_R(y) \forall i \in I$ .

$\Rightarrow p_i(x) = p_i(y) \forall i \in I \Rightarrow x(i) = y(i) \forall i \in I \Rightarrow x = y$ . Let  $(\alpha, \beta) \in \bigcap_{i \in I} \sigma_i$

where  $\alpha, \beta \in \Gamma$ . Then  $p'_i|_\Gamma(\alpha) = p'_i|_\Gamma(\beta) \forall i \in I \Rightarrow p'_i(\alpha) = p'_i(\beta) \forall i \in I \Rightarrow \alpha(i) = \beta(i) \forall i \in I \Rightarrow \alpha = \beta$ . Hence  $\bigcap_{i \in I} (\theta_i, \sigma_i) = (0_R, 0_\Gamma)$ .

(ii) Let  $\bar{x} := (x_i : i \in I) \in R^I \ni (x_i, x_j) \in \phi \forall i, j \in I$ . Put  $x := \langle x_i(i) : i \in I \rangle$ . So  $x \in R, x_i \in R$  and  $x(i) = x_i(i) \forall i \in I \Rightarrow p_i|_R(x) = p_i|_R(x_i) \forall i \in I \Rightarrow (x, x_i) \in \theta_i \forall i \in I$ . Hence  $\exists x \in R \ni (x, x_i) \in \theta_i, \forall i \in I$ .

(iii) Let  $\bar{\alpha} := (\alpha_i : i \in I) \in \Gamma^I \ni (\alpha_i, \alpha_j) \in \rho \forall i, j \in I$ . Put  $\alpha := \langle \alpha_i(i) : i \in I \rangle$ . So  $\alpha \in \Gamma, \alpha_i \in \Gamma$  and  $\alpha(i) = \alpha_i(i) \forall i \in I \Rightarrow p'_i|_\Gamma(\alpha) = p'_i|_\Gamma(\alpha_i) \forall i \in I \Rightarrow (\alpha, \alpha_i) \in \sigma_i \forall i \in I$ . Hence  $\exists \alpha \in \Gamma \ni (\alpha, \alpha_i) \in \sigma_i, \forall i \in I$ .

(iv). Define  $f : R/\theta_i \rightarrow R_i$  by  $[a]_{\theta_i} \mapsto a(i)$  and  $g : \Gamma/\sigma_i \rightarrow \Gamma_i$  by  $[\alpha]_{\sigma_i} \mapsto \alpha(i)$ . Note that for any  $[a]_{\theta_i}, [b]_{\theta_i} \in R/\theta_i, [a]_{\theta_i} = [b]_{\theta_i} \Leftrightarrow (a, b) \in \theta_i \Leftrightarrow p_i|_R(a) = p_i|_R(b) \Leftrightarrow a(i) = b(i) \Leftrightarrow f([a]_{\theta_i}) = f([b]_{\theta_i})$  and for any  $[\alpha]_{\sigma_i}, [\beta]_{\sigma_i} \in \Gamma/\sigma_i, [\alpha]_{\sigma_i} = [\beta]_{\sigma_i} \Leftrightarrow (\alpha, \beta) \in \sigma_i \Leftrightarrow p'_i|_\Gamma(\alpha) = p'_i|_\Gamma(\beta) \Leftrightarrow \alpha(i) = \beta(i) \Leftrightarrow g([\alpha]_{\sigma_i}) = g([\beta]_{\sigma_i})$ . Therefore  $(f, g)$  is well defined and one-one. For any  $a_i \in R_i$  and  $\alpha_i \in \Gamma_i, \exists a \in R$  and  $\alpha \in \Gamma \ni a(i) = p_i|_R(a) = a_i$  and  $\alpha(i) = p'_i|_\Gamma(\alpha) = \alpha_i$ . Now  $[a]_{\theta_i} \in R/\theta_i, [\alpha]_{\sigma_i} \in \Gamma/\sigma_i$  and  $f([a]_{\theta_i}) = a(i) = a_i, g([\alpha]_{\sigma_i}) = \alpha(i) = \alpha_i$ . Hence  $(f, g)$  is onto.

To prove  $(f, g)$  is a homomorphism, let  $([x_j]_{\theta_i} : j \in J)$  be a summable family in  $R/\theta_i$ . Then  $f(\sum_{j \in J} [x_j]_{\theta_i}) = f([\sum_j x_j]_{\theta_i}) = (\sum_j x_j)(i) = \sum_j f([x_j]_{\theta_i})$ . Let  $([\alpha_j]_{\sigma_i} : j \in J)$  be a summable family in  $\Gamma/\sigma_i$ . Then  $g(\sum_{j \in J} [\alpha_j]_{\sigma_i}) = g([\sum_j \alpha_j]_{\sigma_i}) = (\sum_j \alpha_j)(i) = \sum_j g([\alpha_j]_{\sigma_i})$ . Now for any  $[a]_{\theta_i}, [b]_{\theta_i} \in R/\theta_i$  and  $[\alpha]_{\sigma_i} \in \Gamma/\sigma_i$ ,  $f([a]_{\theta_i}[\alpha]_{\sigma_i}[b]_{\theta_i}) = f([a\alpha b]_{\theta_i}) = (a\alpha b)(i) = a(i)\alpha(i)b(i) = f([a]_{\theta_i})g([\alpha]_{\sigma_i})f([b]_{\theta_i})$  and hence  $(f, g)$  is a homomorphism from  $(R/\theta_i, \Gamma/\sigma_i)$  onto  $(R_i, \Gamma_i)$ ,  $i \in I$ . Hence  $(R/\theta_i, \Gamma/\sigma_i) \cong (R_i, \Gamma_i)$ ,  $i \in I$ .  $\square$

**Corollary 4.7.** Let  $\{R_i \mid i \in I\}$  be a family of  $\Gamma$ -so-rings,  $R$  be a  $\Gamma$ -sub so-ring of  $\prod_{i \in I} R_i$  and let  $\phi \in \text{Con}R$ . For  $i \in I$ , let  $\theta_i$  be the kernel of the projection at  $i$ , restricted to  $R$ . If  $R$  is a  $\phi$ -product of  $R_i$ ,  $i \in I$ , then

- (i)  $0_R = \bigcap_{i \in I} \theta_i$ ,
- (ii) for every  $\bar{x} = (x_i : i \in I) \in R^I$ , if  $(x_i, x_j) \in \phi \forall i, j \in I$ , then  $\exists x \in R \ni (x, x_i) \in \theta_i, \forall i \in I$ ,
- (iii)  $R/\theta_i \cong R_i \forall i \in I$ .

**Definition 4.8.** Let  $R$  be a  $\Gamma$ -so-ring and let  $(\phi, \rho) \in \text{Con}(R, \Gamma)$ . For any family  $\{(\theta_i, \sigma_i) \mid i \in I\}$  of congruence relations on  $(R, \Gamma)$ , we write  $(0_R, 0_\Gamma) = \Pi_{(\phi, \rho)}((\theta_i, \sigma_i) : i \in I)$  if and only if the conditions (i),(ii) and (iii) of above theorem are satisfied.

**Definition 4.9.** Let  $R$  be a  $\Gamma$ -so-ring and let  $\phi \in \text{Con}R$ . For any family  $\{\theta_i \mid i \in I\}$  of  $\Gamma$ -congruence relations on  $R$ , we write  $0_R = \Pi_\phi(\theta_i : i \in I)$  if and only if the conditions (i) and (ii) of above corollary are satisfied.

**Remark 4.10.** Let  $R$  be a  $\Gamma$ -so-ring and let  $\{(\theta_i, \sigma_i) \mid i \in I\}$  be a family of congruence relations on  $(R, \Gamma)$ . Then

- (i)  $(0_R, 0_\Gamma) = \Pi_{(0_R, 0_\Gamma)}((\theta_i, \sigma_i) : i \in I)$  if and only if  $(0_R, 0_\Gamma) = \bigcap_{i \in I} (\theta_i, \sigma_i)$ ,
- (ii)  $(0_R, 0_\Gamma) = \Pi_{(1_R, 1_\Gamma)}((\theta_i, \sigma_i) : i \in I)$  if and only if  $(0_R, 0_\Gamma) = \bigcap_{i \in I} (\theta_i, \sigma_i)$ , for every  $(x_i : i \in I) \in R^I$ ,  $\exists x \in R \ni (x, x_i) \in \theta_i$  and for every  $(\alpha_i : i \in I) \in \Gamma^I$ ,  $\exists \alpha \in \Gamma \ni (\alpha, \alpha_i) \in \sigma_i \forall i \in I$ .

**Remark 4.11.** Let  $R$  be a  $\Gamma$ -so-ring and let  $\{\theta_i \mid i \in I\}$  be a family of  $\Gamma$ -congruence relations on  $R$ . Then

- (i)  $0_R = \Pi_{0_R}(\theta_i : i \in I)$  if and only if  $0_R = \bigcap_{i \in I} \theta_i$ ,
- (ii)  $0_R = \Pi_{1_R}(\theta_i : i \in I)$  if and only if  $0_R = \bigcap_{i \in I} \theta_i$  and for every  $(x_i : i \in I) \in R^I$ ,

$\exists x \in R \ni (x, x_i) \in \theta_i \forall i \in I.$

**Definition 4.12.** Let  $R$  be a  $\Gamma$ -so-ring and  $R'$  be a  $\Gamma'$ -so-ring. Suppose  $(f, g)$  is an epimorphism from  $(R, \Gamma)$  onto  $(R', \Gamma')$ . For any congruence relation  $(\phi, \rho)$  on  $(R, \Gamma)$ , define  $(f(\phi), g(\rho)) = (\{(f(x), f(y)) \mid (x, y) \in \phi\}, \{(g(\alpha), g(\beta)) \mid (\alpha, \beta) \in \rho\})$ .

It can be easily observed that the relation  $(f(\phi), g(\rho))$  is a congruence relation on  $(R', \Gamma')$ .

**Lemma 4.13.** Let  $R$  be a  $\Gamma$ -so-ring,  $R'$  be a  $\Gamma'$ -so-ring and  $(\phi, \rho), \{(\theta_i, \sigma_i) \mid i \in I\}$  be a family of congruence relations on  $(R, \Gamma)$ . If  $(f, g)$  is an isomorphism from  $(R, \Gamma)$  onto  $(R', \Gamma')$ , then  $(0_R, 0_\Gamma) = \Pi_{(\phi, \rho)}((\theta_i, \sigma_i) : i \in I)$  if and only if  $(0_{R'}, 0_{\Gamma'}) = \Pi_{(f(\phi), g(\rho))}((f(\theta_i), g(\sigma_i)) : i \in I)$ .

*Proof.* Suppose  $(0_R, 0_\Gamma) = \Pi_{(\phi, \rho)}((\theta_i, \sigma_i) : i \in I)$ . Since  $(\phi, \rho)$  and  $\{(\theta_i, \sigma_i) \mid i \in I\}$  are congruence relations on  $(R, \Gamma)$ ,  $(f(\phi), g(\rho))$  and  $\{(f(\theta_i), g(\sigma_i)) \mid i \in I\}$  are also congruence relations on  $(R', \Gamma')$ . Let  $(f(x), f(y)) \in \bigcap_{i \in I} f(\theta_i)$  and  $(g(\alpha), g(\beta)) \in \bigcap_{i \in I} g(\sigma_i)$ . Then  $(x, y) \in \bigcap_{i \in I} \theta_i = 0_R$  and  $(\alpha, \beta) \in \bigcap_{i \in I} \sigma_i = 0_\Gamma \Rightarrow x = y$  and  $\alpha = \beta \Rightarrow f(x) = f(y)$  and  $g(\alpha) = g(\beta)$ . Therefore  $\bigcap_{i \in I} (f(\theta_i), g(\sigma_i)) = (0_{R'}, 0_{\Gamma'})$ . Let  $\bar{y} := (y_i : i \in I) \in R'^I \ni (y_i, y_j) \in f(\phi) \forall i, j \in I$ . Since  $f$  is onto,  $\exists \bar{x} := (x_i : i \in I) \in R^I \ni f(x_i) = y_i \forall i \in I$  &  $(x_i, x_j) \in \phi \forall i, j \in I \Rightarrow \exists x \in R \ni (x, x_i) \in \theta_i \forall i \in I \Rightarrow \exists y := f(x) \in R' \ni (y, y_i) \in f(\theta_i) \forall i \in I$ . Let  $\bar{\beta} := (\beta_i : i \in I) \in \Gamma'^I \ni (\beta_i, \beta_j) \in g(\rho) \forall i, j \in I$ . Since  $g$  is onto,  $\exists \bar{\alpha} := (\alpha_i : i \in I) \in \Gamma^I \ni g(\alpha_i) = \beta_i \forall i \in I$  &  $(\alpha_i, \alpha_j) \in \rho \forall i, j \in I \Rightarrow \exists \alpha \in \Gamma \ni (\alpha, \alpha_i) \in \sigma_i \forall i \in I \Rightarrow \exists \beta := g(\alpha) \in \Gamma' \ni (\beta, \beta_i) \in g(\sigma_i) \forall i \in I$ . Hence  $(0_{R'}, 0_{\Gamma'}) = \Pi_{(f(\phi), g(\rho))}((f(\theta_i), g(\sigma_i)) : i \in I)$ .

Suppose  $(0_{R'}, 0_{\Gamma'}) = \Pi_{(f(\phi), g(\rho))}((f(\theta_i), g(\sigma_i)) : i \in I)$ . Let  $(x, y) \in \bigcap_{i \in I} \theta_i$  and  $(\alpha, \beta) \in \bigcap_{i \in I} \sigma_i$ . Then  $(f(x), f(y)) \in \bigcap_{i \in I} f(\theta_i) = 0_{R'}$  and  $(g(\alpha), g(\beta)) \in \bigcap_{i \in I} g(\sigma_i) = 0_{\Gamma'} \Rightarrow f(x) = f(y)$  and  $g(\alpha) = g(\beta)$ . Since  $f$  and  $g$  are one-one,  $x = y$  and  $\alpha = \beta$ . Hence  $\bigcap_{i \in I} (\theta_i, \sigma_i) = (0_R, 0_\Gamma)$ . Let  $\bar{x} := (x_i : i \in I) \in R^I \ni$

$(x_i, x_j) \in \phi \forall i, j \in I$ . Then  $\bar{y} := (f(x_i) : i \in I) \in R'^I \ni (f(x_i), f(x_j)) \in f(\phi) \forall i, j \in I$ . Since  $f$  is onto,  $\exists y \in R' \ni (y, f(x_i)) \in f(\theta_i) \forall i \in I \Rightarrow \exists x \in R \ni f(x) = y$  &  $(x, x_i) \in \theta_i \forall i \in I$ . Let  $\bar{\alpha} := (\alpha_i : i \in I) \in \Gamma^I \ni (\alpha_i, \alpha_j) \in \rho \forall i, j \in I$ . Then  $\bar{\beta} := (g(\alpha_i) : i \in I) \in \Gamma'^I \ni (g(\alpha_i), g(\alpha_j)) \in g(\sigma_i) \forall i, j \in I$ . Since  $g$  is onto,  $\exists \beta \in \Gamma' \ni (\beta, g(\alpha_i)) \in g(\sigma_i) \forall i \in I \Rightarrow \exists \alpha \in$

$\Gamma \ni g(\alpha) = \beta \ \& \ (\alpha, \alpha_i) \in \rho \ \forall i \in I$ . Hence  $(0_R, 0_\Gamma) = \Pi_{(\phi, \rho)}((\theta_i, \sigma_i) : i \in I)$ .  $\square$

**Corollary 4.14.** *Let  $R$  and  $R'$  be  $\Gamma$ -so-rings and  $\phi, \theta_i (i \in I)$  be a family  $\Gamma$ -congruence relations on  $R$ . If  $f$  is a  $\Gamma$ -isomorphism from  $R$  onto  $R'$ , then  $0_{R'} = \Pi_{\phi}(\theta_i : i \in I)$  if and only if  $0_{R'} = \Pi_{f(\phi)}(f(\theta_i) : i \in I)$ .*

**Theorem 4.15.** *Let  $R$  be a  $\Gamma$ -so-ring,  $(\phi, \rho) \in Con(R, \Gamma)$  and  $\{(\theta_i, \sigma_i) \mid i \in I\}$  be a family of congruence relations on  $(R, \Gamma)$  such that  $(0_R, 0_\Gamma) = \Pi_{(\phi, \rho)}((\theta_i, \sigma_i) : i \in I)$ . If the mappings  $f : R \rightarrow \prod_{i \in I} R/\theta_i$  and  $g : \Gamma \rightarrow \prod_{i \in I} \Gamma/\sigma_i$  are defined by  $f(x) = ([x]_{\theta_i} : i \in I)$  and  $g(\alpha) = ([\alpha]_{\sigma_i} : i \in I)$  respectively, then  $(f(R), g(\Gamma))$  is a  $(f(\phi), g(\rho))$ -product of  $(R/\theta_i, \Gamma/\sigma_i), i \in I$ .*

*Proof.* By the proof of the Lemma 3.7,  $(f, g)$  is a monomorphism from  $(R, \Gamma)$  into  $\prod_{i \in I} (R/\theta_i, \Gamma/\sigma_i)$  and  $(f(R), g(\Gamma))$  is a subdirect product of  $(R/\theta_i, \Gamma/\sigma_i), i \in I$ . Let  $(y_i : i \in I) \in f(R)^I \ni (y_i, y_j) \in f(\phi) \ \forall i, j \in I$ . Then  $\exists x_i \in R \ \forall i \in I \ni f(x_i) = y_i \ \& \ (x_i, x_j) \in \phi \ \forall i, j \in I \Rightarrow \exists x \in R \ni (x, x_i) \in \theta_i \ \forall i \in I \Rightarrow [x]_{\theta_i} = [x_i]_{\theta_i} \ \forall i \in I \Rightarrow f(x)(i) = f(x_i)(i) = y_i(i) \ \forall i \in I$  and hence  $(y_i(i) : i \in I) = f(x) \in f(R)$ . Let  $(\beta_i : i \in I) \in g(\Gamma)^I \ni (\beta_i, \beta_j) \in g(\rho) \ \forall i, j \in I$ . Then  $\exists \alpha_i \in \Gamma \ \forall i \in I \ni g(\alpha_i) = \beta_i \ \& \ (\alpha_i, \alpha_j) \in \rho \ \forall i, j \in I \Rightarrow \exists \alpha \in \Gamma \ni (\alpha, \alpha_i) \in \sigma_i \ \forall i \in I \Rightarrow [\alpha]_{\sigma_i} = [\alpha_i]_{\sigma_i} \ \forall i \in I \Rightarrow g(\alpha)(i) = g(\alpha_i)(i) = \beta_i(i) \ \forall i \in I$  and hence  $(\beta_i(i) : i \in I) = g(\alpha) \in g(\Gamma)$ . Hence  $(f(R), g(\Gamma))$  is a  $(f(\phi), g(\rho))$ -product of  $(R/\theta_i, \Gamma/\sigma_i), i \in I$ .  $\square$

**Corollary 4.16.** *Let  $R$  be a  $\Gamma$ -so-ring,  $\phi \in ConR$  and  $\{\theta_i \mid i \in I\}$  be a family of  $\Gamma$ -congruence relations on  $R$  such that  $0_R = \Pi_{\phi}(\theta_i : i \in I)$ . If the mapping  $f : R \rightarrow \prod_{i \in I} R/\theta_i$  is defined by  $f(x) = ([x]_{\theta_i} : i \in I) \ \forall x \in R$ , then  $f(R)$  is a  $f(\phi)$ -product of  $R/\theta_i, i \in I$ .*

**Definition 4.17.** Let  $R$  be a  $\Gamma$ -so-ring,  $\{R_i \mid i \in I\}$  be a family of  $\Gamma_i$ -so-rings and  $(\phi, \rho) \in Con(R, \Gamma)$ . If  $(f, g)$  is a monomorphism of  $(R, \Gamma)$  into  $\prod_{i \in I} (R_i, \Gamma_i)$  and if  $(f(R), g(\Gamma))$  is a  $(f(\phi), g(\rho))$ -product of  $(R_i, \Gamma_i), i \in I$ , then the ordered pair  $\langle ((R_i, \Gamma_i) : i \in I), (f, g) \rangle$  is called a  $(\phi, \rho)$ -representation of  $(R, \Gamma)$ .

**Definition 4.18.** Let  $R, R_i (i \in I)$  be a family of  $\Gamma$ -so-rings and  $\phi \in ConR$ . If  $f$  is a  $\Gamma$ -monomorphism of  $R$  into  $\prod_{i \in I} R_i$  and if  $f(R)$  is a  $f(\phi)$ -product of  $R_i, i \in I$ , then the ordered pair  $\langle (R_i : i \in I), f \rangle$  is called a  $\phi$ -representation of  $R$ .

**Remark 4.19.** Let  $R$  be a  $\Gamma$ -so-ring and  $\{R_i \mid i \in I\}$  be a family of  $\Gamma_i$ -so-rings. Suppose  $(f, g)$  is a monomorphism from  $(R, \Gamma)$  into  $\prod_{i \in I} (R_i, \Gamma_i)$ . Then

- (i)  $\langle ((R_i, \Gamma_i) : i \in I), (f, g) \rangle$  is a  $(0_R, 0_\Gamma)$ -representation of  $(R, \Gamma)$  if and only if  $(f(R), g(\Gamma))$  is a subdirect product of  $(R_i, \Gamma_i)$ ,  $i \in I$ ,
- (ii)  $\langle ((R_i, \Gamma_i) : i \in I), (f, g) \rangle$  is a  $(1_R, 1_\Gamma)$ -representation of  $(R, \Gamma)$  if and only if  $(f(R), g(\Gamma))$  is the direct product of  $(R_i, \Gamma_i)$ ,  $i \in I$ .

**Remark 4.20.** Let  $R$  and  $R_i (i \in I)$  be a family of  $\Gamma$ -so-rings. Suppose  $f$  is a  $\Gamma$ -monomorphism from  $R$  into  $\prod_{i \in I} R_i$ . Then

- (i)  $\langle (R_i : i \in I), f \rangle$  is a  $0_R$ -representation of  $R$  if and only if  $f(R)$  is a  $\Gamma$ -subdirect product of  $R_i$ ,  $i \in I$ ,
- (ii)  $\langle (R_i : i \in I), f \rangle$  is a  $1_R$ -representation of  $R$  if and only if  $f(R)$  is the  $\Gamma$ -direct product of  $R_i$ ,  $i \in I$ .

**Theorem 4.21.** Let  $R$  be a  $\Gamma$ -so-ring,  $(\phi, \rho) \in \text{Con}(R, \Gamma)$  and  $\{(\theta_i, \sigma_i) \mid i \in I\}$  be a family of congruence relations on  $(R, \Gamma)$ . If the mappings  $f : R \rightarrow \prod_{i \in I} R/\theta_i$

and  $g : \Gamma \rightarrow \prod_{i \in I} \Gamma/\sigma_i$  are defined by  $f(x) = ([x]_{\theta_i} : i \in I)$  and  $g(\alpha) = ([\alpha]_{\sigma_i} : i \in I)$  respectively, then  $\langle ((R/\theta_i, \Gamma/\sigma_i) : i \in I), (f, g) \rangle$  is a  $(\phi, \rho)$ -representation of  $(R, \Gamma) \Leftrightarrow (0_R, 0_\Gamma) = \Pi_{(\phi, \rho)}((\theta_i, \sigma_i) : i \in I)$ .

*Proof.* Suppose  $\langle ((R/\theta_i, \Gamma/\sigma_i) : i \in I), (f, g) \rangle$  is a  $(\phi, \rho)$ -representation of  $(R, \Gamma)$ . Then  $(f(R), g(\Gamma))$  is a  $(f(\phi), g(\rho))$ -product of  $(R/\theta_i, \Gamma/\sigma_i)$ ,  $i \in I$ . Note that  $(f(x), f(y)) \in f(\theta_i) \Leftrightarrow (x, y) \in \theta_i \Leftrightarrow [x]_{\theta_i} = [y]_{\theta_i} \Leftrightarrow p_i \mid_{f(R)} (f(x)) = p_i \mid_{f(R)} (f(y)) \Leftrightarrow (f(x), f(y)) \in \ker(p_i \mid_{f(R)})$ . Also note that  $(g(\alpha), g(\beta)) \in g(\sigma_i) \Leftrightarrow (\alpha, \beta) \in \sigma_i \Leftrightarrow [\alpha]_{\sigma_i} = [\beta]_{\sigma_i} \Leftrightarrow p'_i \mid_{g(\Gamma)} (g(\alpha)) = p'_i \mid_{g(\Gamma)} (g(\beta)) \Leftrightarrow (g(\alpha), g(\beta)) \in \ker(p'_i \mid_{g(\Gamma)})$ . Therefore  $(f(\theta_i), g(\sigma_i))$ ,  $i \in I$  are the kernels of the projections at  $i$  restricted to  $(f(R), g(\Gamma))$ . Then by the Theorem 4.6,  $(0_{f(R)}, 0_{g(\Gamma)}) = \bigcap ((f(\theta_i), g(\sigma_i)) : i \in I)$ . Hence  $(0_{f(R)}, 0_{g(\Gamma)}) = \prod_{(f(\phi), g(\rho))} ((f(\theta_i), g(\sigma_i)) : i \in I)$ . By the Lemma 4.13,  $(0_R, 0_\Gamma) = \Pi_{(\phi, \rho)}((\theta_i, \sigma_i) : i \in I)$ . The converse part is trivial in view of the Theorem 4.15. Hence the theorem.  $\square$

**Corollary 4.22.** Let  $R$  be a  $\Gamma$ -so-ring,  $\phi, \theta_i (i \in I) \in \text{Con}R$ . Define  $f : R \rightarrow \prod R/\theta_i$  by  $x \mapsto ([x]_{\theta_i} : i \in I)$ . Then  $\langle (R/\theta_i : i \in I), f \rangle$  is a  $\phi$ -representation of  $R$  if and only if  $0_R = \prod_{\phi}(\theta_i : i \in I)$ .

**Remark 4.23.** (i) A family  $\{(\theta_i, \sigma_i) \mid i \in I\}$  of congruence relations on a  $\Gamma$ -so-ring  $R$  gives a subdirect representation if and only if  $\bigcap_{i \in I} (\theta_i, \sigma_i) = (0_R, 0_\Gamma)$ .

(ii) A family  $\{(\theta_i, \sigma_i) \mid i \in I\}$  of congruence relations on a  $\Gamma$ -so-ring  $R$  constitutes a direct representation if and only if  $(0_R, 0_\Gamma) = \prod_{(1_R, 1_\Gamma)} ((\theta_i, \sigma_i) : i \in I)$ .

**Remark 4.24.** (i) A family  $\{\theta_i \mid i \in I\}$  of  $\Gamma$ -congruence relations on a  $\Gamma$ -so-ring  $R$  gives a  $\Gamma$ -subdirect representation if and only if  $\bigcap_{i \in I} \theta_i = 0_R$ .

(ii) A family  $\{\theta_i \mid i \in I\}$  of  $\Gamma$ -congruence relations on a  $\Gamma$ -so-ring  $R$  constitutes a  $\Gamma$ -direct representation if and only if  $0_R = \prod_{1_R} (\theta_i : i \in I)$ .

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