\textbf{I}_2\text{-ASYMPTOTICALLY LACUNARY STATISTICAL EQUIVALENCE OF WEIGHT } g \text{ OF DOUBLE SEQUENCES OF SETS}

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\textsc{Abstract.} In this paper, our aim is to introduce new notions, namely, Wijsman asymptotically \textit{I}_2\text{-statistical equivalence of weight } g, \text{ Wijsman strongly asymptotically } \mathcal{I}_2\text{-lacunary equivalence of weight } g \text{ and Wijsman asymptotically } \mathcal{I}_2\text{-lacunary statistical equivalence of weight } g \text{ of double set sequences. We mainly investigate their relationship and also make some observations about these classes.}

1. Introduction

Theory of statistical convergence was firstly originated by Fast [6]. This concept was extended to the double sequences by Mursaleen and Edely [14]. Lacunary statistical convergence was defined by Fridy and Orhan [7]. Çakan and Altay [3] presented multidimensional analogues of the results presented by Fridy and Orhan [7].

The idea of \textit{I}-convergence was introduced by Kostyrko et al. [11] as a generalization of statistical convergence which is based on the structure of the ideal \textit{I} of subset of the set of natural numbers. Recently, Das et al. [5] introduced new notions, namely \textit{I}-statistical convergence and \textit{I}-lacunary statistical convergence by using ideal. The notion of lacunary ideal convergence of real sequences was introduced in [23].

Das, Koystrko, Wilczynski and Malik [4] introduced the concept of \textit{I}-convergence of double sequences in a metric space and studied some properties of this convergence. Belen et al. [2] introduced the notion of ideal statistical convergence of double sequences, which is a new generalization of the notions of statistical convergence and usual convergence. Kumar et al. [12] introduced \textit{I}-lacunary statistical convergence of double sequences.

Nuray and Rhoades [15] extended the notion of convergence of set sequences to statistical convergence and gave some basic theorems. Ulusu and Nuray [24] defined the Wijsman lacunary statistical convergence of sequence

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of sets and considered its relation with Wijsman statistical convergence. Kişi and Nuray [8] introduced a new convergence notion, for sequences of sets, which is called Wijsman $I$-convergence by using ideal. Recently, Ulusu and Dündar [26] studied the concepts of Wijsman $I$-statistical convergence, Wijsman $I$-lacunary statistical convergence and Wijsman strongly $I$-lacunary convergence of sequences of sets.

Nuray et al. [16] studied Wijsman statistical convergence, Hausdorff statistical convergence and Wijsman statistical Cauchy double sequences of sets and investigate the relationship between them. Kişi [10] introduced the concepts of the Wijsman $I_2$-statistical convergence, Wijsman $I_2$-lacunary statistical convergence and Wijsman strongly $I_2$-lacunary convergence of double sequences of sets and investigate the relationship between them.

Asymptotic equivalence of sequences was introduced by Pobyvanets [18]; Marouf’s work [13] was extension of Pobyvanets’s work. In 2003, Patterson [19] extended these concepts by presenting an asymptotically statistical equivalent analog of these definitions and natural regularity conditions for nonnegative summability matrices.

In [17] asymptotically lacunary statistical equivalent which is a natural combination of the definitions for asymptotically equivalent, statistical convergence and lacunary sequences was studied. Also in [20], $I$-asymptotically statistical equivalent and $I$-asymptotically lacunary statistical equivalent sequences were examined.

The concept of asymptotically equivalence of sequences of real numbers which is defined by Marouf [13] has been extended by Ulusu and Nuray [25] to concept of Wijsman asymptotically equivalence of set sequences. In addition to these definitions, natural inclusion theorems are presented. Kişi et al. [9] introduced the concept of Wijsman $I$-asymptotically equivalence of sequences of sets.

Now, we recall the basic definitions and concepts.

The upper density of weight $g$ was defined in [1] by the formula
\[ d_g^*(A) = \lim_{n \to \infty} \sup_{1 \leq k \leq n} \frac{A(1,n)}{g(n)} \]
for $A \subseteq \mathbb{N}$ where as before $A(1,n)$ denotes the cardinality of the set $A \cap [1,n]$. Then, the family
\[ I_g = \{ A \subseteq \mathbb{N} : d_g^*(A) = 0 \} \]
forms an ideal. It has been observed in [1] that $\mathbb{N} \in I_g$ if and only if $\frac{n}{g(n)} \to 0$ as $n \to \infty$. So we additionally assume that $\frac{n}{g(n)} \to 0$ as $n \to \infty$ so that $\mathbb{N} \notin I_g$ and $I_g$ is a proper admissible ideal of $\mathbb{N}$. The collection of all such weight functions $g$ satisfying the above properties will be denoted by $G$. As a natural consequence we can introduce the following definition.
Definition 1.1. ([1]) A sequence \( \{x_n\} \) of real numbers is said to be statistically convergent to \( x \) if for any given \( \varepsilon > 0 \), \( \hat{d}_g(A_{\varepsilon}) = 0 \), where \( A_{\varepsilon} \) is the set defined in Definition 1.3.

Savaş [21] introduced new notions, namely, \( I \)-statistical double convergence of weight \( g \) and \( I \)-lacunary double statistical convergence of weight \( g \) and investigated their relationship and also make some observations about these classes.

A double sequence \( x = (x_{k,l}) \) has a Pringsheim limit \( L \) (denoted by \( P - \lim x = L \)) provided that given an \( \varepsilon > 0 \), there exists a \( n \in \mathbb{N} \) such that \( |x_{k,l} - L| < \varepsilon \), whenever \( k, l > n \). We describe such an \( x = (x_{k,l}) \) more briefly as "P-convergent".

The double sequence \( \{A_{k,l}\} \) is Wijsman convergent to \( A \), if for each \( x \in X \),

\[
\lim_{k,l \to \infty} d(x, A_{k,l}) = d(x, A) \text{ or } \lim_{k,l \to \infty} d(x, A_{k,l}) = d(x, A).
\]

In this case we write \( W_2 - \lim A_{k,l} = A \).

We define \( d(x; A_{k,j}, B_{k,j}) \) as follows:

\[
d(x; A_{k,j}, B_{k,j}) = \begin{cases} d(x, A_{k,j}) & \text{if } x \notin A_{k,j} \cup B_{k,j} \\ L & \text{if } x \in A_{k,j} \cup B_{k,j} \end{cases}
\]

The double sequences \( \{A_{k,j}\} \) and \( \{B_{k,j}\} \) are Wijsman asymptotically equivalent of multiple \( L \) if every \( \varepsilon > 0 \), for each \( x \in X \), \( \lim_{k,j \to \infty} d(x; A_{k,j}, B_{k,j}) = L \).

The double sequences \( \{A_{k,j}\} \) and \( \{B_{k,j}\} \) are said to be asymptotically statistical equivalent of multiple \( L \) if every \( \varepsilon > 0 \), for each \( x \in X \),

\[
\lim_{m,n \to \infty} \frac{1}{mn} \left| \left\{ k \leq m, j \leq n : |d(x; A_{k,j}, B_{k,j}) - L| \geq \varepsilon \right\} \right| = 0.
\]

Throughout the paper, we shall denoted by \( \mathcal{I}_2 \) be an admissible ideal of \( \mathbb{N} \times \mathbb{N} \).

A double sequence \( \bar{\theta} = \theta_{ru} = \{(k_r, j_u)\} \) is called double lacunary sequence if there exist two increasing sequences of integers \( (k_r) \) and \( (j_u) \) such that

\[
k_0 = 0, \ h_r = k_r - k_{r-1} \to \infty \text{ as } r \to \infty
\]

\[
j_0 = 0, \ h_u = j_u - j_{u-1} \to \infty, \text{ as } u \to \infty.
\]

We will use the following notation \( k_{ru} := k_r j_u, \ h_{ru} := h_r \bar{u} \) and \( \theta_{ur} \) is determined by

\[
I_{ur} := \{(k, j) : k_{r-1} < k \leq k_r \text{ and } j_{u-1} < j \leq j_u\},
\]

\[
q_r := \frac{k_r}{k_{r-1}}, \ q_u := \frac{j_u}{j_{u-1}} \text{ and } q_{ru} := q_r q_u.
\]
Throughout the paper, by $\theta_2 = \theta_{ru} = \{(k_r, j_u)\}$ we will denote a double lacunary sequence of positive real numbers, respectively, unless otherwise stated.

Let $\theta_{ru}$ be a double lacunary sequence and $\mathcal{I}_2 \subseteq \mathcal{P}(\mathbb{N} \times \mathbb{N})$ be a non-trivial ideal.

**Definition 1.2.** ([27]) The double sequences $\{A_{kj}\}$ and $\{B_{kj}\}$ are Wijsman asymptotically $\mathcal{I}_2$-equivalent of multiple $L$ if for every $\varepsilon > 0$, for each $x \in X$,

$$\{(k, j) \in \mathbb{N} \times \mathbb{N}: |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon\} \in \mathcal{I}_2.$$  

In this case, we write $A_{kj} \overset{(\mathcal{I}_2^L)}{\sim} B_{kj}$ and simply Wijsman asymptotically $\mathcal{I}_2$-equivalent if $L = 1$.

2. Main Results

Asymptotically $\mathcal{I}_2$-lacunary statistical equivalence of double sequences of sets was studied by Ulusu and Dündar [27]. It is natural question that whether this concept will be work for Wijsman asymptotically $\mathcal{I}_2$-lacunary statistical equivalence of weight $g$. In this paper, we gave some answers of this question and also we prove that Wijsman asymptotically $\mathcal{I}_2$-lacunary statistical equivalence a better tool than Wijsman asymptotically lacunary statistical equivalence.

In this section, we define the concepts of Wijsman asymptotically $\mathcal{I}_2$-statistical equivalence of weight $g$, Wijsman strongly asymptotically $\mathcal{I}_2$-lacunary equivalence of weight $g$ and Wijsman asymptotically $\mathcal{I}_2$-lacunary statistical equivalence of weight $g$ of double sequences of sets and investigate the relationship between them.

**Definition 2.1.** The double sequences $\{A_{kj}\}$ and $\{B_{kj}\}$ are Wijsman asymptotically $\mathcal{I}_2$-statistical equivalent of weight $g$ of multiple $L$ if for every $\varepsilon > 0$, $\delta > 0$ and for each $x \in X$,

$$\left\{ \left( m, n \right) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(mn)} \left\{ k \leq m, j \leq n : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\} \geq \delta \right\} \in \mathcal{I}_2.$$  

In this case, we write $A_{kj} \overset{S(\mathcal{I}_2^L)}{\sim} B_{kj}$ and simply Wijsman asymptotically $\mathcal{I}_2$-statistical equivalent of weight $g$ equivalent if $L = 1$. The set of Wijsman asymptotically $\mathcal{I}_2$-statistical equivalent double sequences of weight $g$ will be denoted $\{S(\mathcal{I}_2^L)^g\}$.

For $\mathcal{I}_2 = \mathcal{I}_2^I$, Wijsman asymptotically $\mathcal{I}_2$-statistical equivalence of weight $g$ of multiple $L$ coincides with Wijsman asymptotically statistical equivalence of multiple $L$.

As an example, consider the following double sequences;
\[ A_{kj} = \begin{cases} \{ (x, y) \in \mathbb{R}^2 : x^2 + y^2 + 2kgy = 0 \}, & \text{if } k \text{ and } j \text{ are a square integer} \\ \{ 1, 1 \}, & \text{otherwise}, \end{cases} \]

and

\[ B_{kj} = \begin{cases} \{ (x, y) \in \mathbb{R}^2 : x^2 + y^2 - 2kgy = 0 \}, & \text{if } k \text{ and } j \text{ are a square integer} \\ \{ 1, 1 \}, & \text{otherwise}. \end{cases} \]

If we take \( I_2 = I_2^f \), since

\[ \left\{ (m, n) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(mn)} \left| \{ (k, j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \} \right| \geq \delta \right\} \in I_2^f, \]

then the double sequences \( \{ A_{kj} \} \) and \( \{ B_{kj} \} \) are Wijsman asymptotically \( I_2 \)-statistical equivalent.

**Definition 2.2.** Let \( \theta_2 = \{ \theta_{ru} \} \) be a double lacunary sequence. The double sequences \( \{ A_{kj} \} \) and \( \{ B_{kj} \} \) are Wijsman asymptotically \( I_2 \)-lacunary statistical equivalent of weight \( g \) of multiple \( L \) if for \( \varepsilon > 0, \delta > 0 \) and for each \( x \in X \),

\[ \left\{ (r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(h_r h_u)} \sum_{(k, j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \} \right\} \in I_2. \]

In this case, we write \( A_{kj} \sim_{\theta_2 (I_2^f)^g} B_{kj} \) and simply Wijsman \( I_2 \)-asymptotically lacunary statistical equivalent of weight \( g \) if \( L = 1 \). The set of Wijsman asymptotically \( I_2 \)-lacunary statistical equivalent double sequences of weight \( g \) will be denoted \( \{ S_{\theta} (I_2^f)^g \} \).

For \( I_2 = I_2^f \), Wijsman \( I_2 \)-asymptotically lacunary statistical equivalence of weight \( g \) of multiple \( L \) coincides with Wijsman asymptotically lacunary statistical equivalence of weight \( g \) of multiple \( L \).

**Definition 2.3.** Let \( \theta_2 = \{ \theta_{ru} \} \) be a double lacunary sequence. The double sequences \( \{ A_{kj} \} \) and \( \{ B_{kj} \} \) are Wijsman strongly asymptotically \( I_2 \)-lacunary equivalent of weight \( g \) of multiple \( L \) provided that for every \( \varepsilon > 0 \), for each \( x \in X \),

\[ \left\{ (r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(h_r h_u)} \sum_{(k, j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\} \in I_2. \]

In this case, we write \( A_{kj} \sim_{\theta_2 (I_2^f)^g} B_{kj} \) and simply Wijsman strongly \( I_2 \)-asymptotically lacunary equivalent of weight \( g \) if \( L = 1 \).

**Theorem 2.4.** Let \( \theta_2 \) be a lacunary sequence. Then,

\[ A_{kj} \sim_{\theta_2 (I_2^f)^g} B_{kj} \Rightarrow A_{kj} \sim_{\theta_2 (I_2^f)^g} B_{kj}, \]
and $A_{kj}^{\sim_{L_2}^{I_{L}^{W,2}}} B_{kj}$ is proper subset of $A_{kj}^{\sim_{L_2}^{I_{L}^{W,2}}} B_{kj}$.

Proof. Suppose that $\{A_{kj}\}$ and $\{B_{kj}\}$ are Wijsman strongly asymptotically $I_2$-lacunary equivalent of weight $g$ of multiple $L$. Given $\varepsilon > 0$ and for each $x \in X$ we can write

$$
\sum_{(k,j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| \geq \sum_{(k,j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| - \varepsilon
$$

and so we get

$$
\frac{1}{g(h_r h_u)} \sum_{(k,j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \cdot |\{(k, j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon\}|.
$$

Hence, for each $x \in X$ and for any $\delta > 0$, we have

$$
\left\{(r, u) \in N \times N : \frac{1}{g(h_r h_u)} |\{(k, j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon\}| \geq \delta\right\}
$$

$$
\subseteq \left\{(r, u) \in N \times N : \frac{1}{g(h_r h_u)} \sum_{(k,j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \delta\right\} \in I_2.
$$

Hence we have $A_{kj}^{\sim_{L_2}^{I_{L}^{W,2}}} B_{kj}$.

Now, let $\{A_{kj}\}$ be defined as follows:

$$
A_{kj} := \begin{pmatrix}
\{1\} & \{2\} & \{3\} & \ldots & \{\sqrt{h_r h_u}\} & \{0\} & \ldots \\
\{2\} & \{2\} & \{3\} & \ldots & \{\sqrt{h_r h_u}\} & \{0\} & \ldots \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots \\
\{2\} & \{\sqrt{h_r h_u}\} & \ldots & \ldots & \{\sqrt{h_r h_u}\} & \{0\} & \ldots \\
\{0\} & \{0\} & \{0\} & \ldots & \{0\} & \{0\} & \ldots \\
\vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \ddots \\
\end{pmatrix}.
$$

For any $\varepsilon > 0,$

$$
\frac{1}{g(h_r h_u)} |\{(k, j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon\}| \leq \frac{\sqrt{h_r h_u}}{g(h_r h_u)}
$$

and consequently for any $\delta > 0$, we get
\[
\left\{(r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(h_r h_u)} |\{(k, j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - 0| \geq \varepsilon\}| \geq \delta \right\}
\leq \left\{(r, u) \in \mathbb{N} \times \mathbb{N} : \frac{\sqrt[r]{n_{ru}}}{g(h_r h_u)} \geq \delta \right\}.
\]

Note that the set on the right hand side is a finite set and so is a member of \(I_2\). Thus \(A_{kj} \sim_{\mathbb{S}_b(I_{W_2})} B_{kj}\) for \(L = 0\). Again observe that
\[
\frac{1}{g(h_r h_u)} \sum_{(k, j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - 0| = \frac{1}{g(h_r h_u)} \frac{\sqrt[r]{n_{ru}} \left(\frac{\sqrt[r]{n_{ru}}}{2g(h_r h_u)} + 1\right)}{2}.
\]

Hence
\[
\left\{(r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(h_r h_u)} \sum_{(k, j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - 0| \geq \frac{1}{4} \right\}
= \left\{(r, u) \in \mathbb{N} \times \mathbb{N} : \frac{\sqrt[r]{n_{ru}} \left(\frac{\sqrt[r]{n_{ru}}}{2g(h_r h_u)} + 1\right)}{2g(h_r h_u)} \geq \frac{1}{2} \right\}
\]
which evidently belongs to \(F(I)\) as \(I\) is admissible. Therefore \(A_{kj} \sim_{\mathbb{S}_b(I_{W_2})} B_{kj}\) for \(L = 0\). \(\square\)

**Theorem 2.5.** Let \(\theta_2\) be a double lacunary sequence and \(d(x, A_{kj}) \mathcal{O}(d(x, B_{kj}))\). Then,
\[
A_{kj} \sim_{\mathbb{S}_b(I_{W_2})} B_{kj} \Rightarrow A_{kj} \sim_{\mathbb{S}_b(I_{W_2})} B_{kj}.
\]

**Proof.** Suppose that \(\{A_{kj}\}\) and \(\{B_{kj}\}\) are Wijsman asymptotically \(I_2\)-lacunary statistical equivalent of weight \(g\) of multiple \(L\) and \(d(x, A_{kj}) \mathcal{O}(d(x, B_{kj}))\). Then there is a \(M > 0\) such that
\[
|d(x; A_{kj}, B_{kj}) - L| \leq M
\]
for each \(x \in X\) and all \(k, j \in \mathbb{N}\). Given \(\varepsilon > 0\), for each \(x \in X\) we get
\[
\frac{1}{g(h_r h_u)} \sum_{(k, j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| =
\]
\[
= \frac{1}{g(h_r h_u)} \sum_{(k, j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L|
\]
\[
\geq \frac{1}{2}
\]
\[
+ \frac{1}{g(h_r h_u)} \sum_{(k, j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L|
\]
\[
\leq \frac{M}{g(h_r h_u)} \left|\left\{(k, j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \frac{\varepsilon}{2}\right\}\right| + \frac{\varepsilon}{2}.
\]
Hence, for each \( x \in X \) we have
\[
\left\{ (r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(h_r h_u)} \sum_{(k,j) \in I_{ru}} |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\}
\subseteq \left\{ (r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(h_r h_u)} \left\{ (k,j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \frac{\varepsilon}{2} \right\} \geq \frac{\varepsilon}{2M} \right\} \in \mathcal{I}_2.
\]

Therefore, \( A_{kj} S_{\theta_2} B_{kj} \). This completes the proof. \( \Box \)

**Theorem 2.6.** For any double lacunary sequence \( \theta_2 \), Wijsman asymptotically \( \mathcal{I}_2 \)-statistical equivalence of weight \( g \) implies Wijsman asymptotically \( \mathcal{I}_2 \)-lacunary statistical equivalence of weight \( g \) if
\[
\liminf_{r} \frac{g(h_r h_u)}{g(k_r u)} > 1.
\]

**Proof.** Since \( \liminf_{r} \frac{g(h_r h_u)}{g(k_r u)} > 1 \), so we can find a \( H > 1 \) such that for sufficiently large \( r, u \) we have \( \frac{g(h_r h_u)}{g(k_r u)} \geq H \).

Since \( A_{kj} S_{\theta_2} B_{kj} \), for every \( \varepsilon > 0 \) and sufficiently large \( r, u \) we have
\[
\frac{1}{g(k_r u)} \left\{ (k \leq k_r, j \leq j_u : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\}
\geq \frac{1}{g(k_r u)} \left\{ (k,j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\}
\geq H \frac{1}{g(h_r h_u)} \left\{ (k,j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\}.
\]

Then, for any \( \delta > 0 \), we get
\[
\left\{ (r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(h_r h_u)} \left\{ (k,j) \in I_{ru} : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\} \geq \delta \right\}
\subseteq \left\{ (r, u) \in \mathbb{N} \times \mathbb{N} : \frac{1}{g(k_r u)} \left\{ k \leq k_r, j \leq j_u : |d(x; A_{kj}, B_{kj}) - L| \geq \varepsilon \right\} \geq H \delta \right\} \in \mathcal{I}_2.
\]

This shows that \( A_{kj} S_{\theta_2} B_{kj} \). \( \Box \)

It is known that double lacunary statistical convergence implies double statistical convergence if and only if \( \lim_{rs} \sup q_{rs} < \infty \) (see \([22]\)). However for arbitrary admissible ideal \( \mathcal{I}_2 \), this is not clear and we leave it as an open problem.

When Wijsman asymptotically \( \mathcal{I}_2 \)-lacunary statistical equivalence of weight \( g \) implies Wijsman asymptotically \( \mathcal{I}_2 \)-statistical equivalence of weight \( g \)?


References


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