LARGE DEVIATIONS FOR THE EMPIRICAL FIELD OF A GIBBS MEASURE

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1. INTRODUCTION

Let $S$ be a finite set and introduce the compact space $\Omega = S^{Z^d}$ of configurations $\omega: Z^d \rightarrow S$. Let $\mathcal{M}(\Omega)$ denote the compact space of probability measures on $\Omega$, and denote by $\mathcal{M}_S(\Omega)$ the subspace consisting of all elements of $\mathcal{M}(\Omega)$ which are invariant under all shifts $\theta_i: \Omega \rightarrow \Omega$, $i \in Z^d$, where $(\theta_i \omega)(j) = \omega(j+i)$. A measure $\mu \in \mathcal{M}(\Omega)$ is called a Gibbs measure if its local conditional probabilities are specified by a stationary interaction potential. Precise definitions and conditions are given in Section 2.

Let us consider a stationary Gibbs measure $\mu \in \mathcal{M}_S(\Omega)$. Denote the cube $\{i = (i_1, ..., i_d) \in Z^d: 0 \leq i_k < n\}$ by $V_n$. Now define the empirical field $\rho_{V_n}$ as the random element of $\mathcal{M}(\Omega)$ given by

$$\rho_{V_n}(\omega) = \frac{1}{n^d} \sum_{i \in V_n} \delta_{\theta_i \omega}$$

with $\delta_\omega$ the unit point mass at $\omega$. The distribution $\mu \circ \rho_{V_n}^{-1}$ of $\rho_{V_n}$ under $\mu$ belongs to $\mathcal{M}_S(\Omega)$. Our principal result is that the sequence

$$\mu \circ \rho_{V_n}^{-1}, \ n = 1, 2, ...$$

satisfies a large deviation principle where the rate function is given by the specific relative entropy $h(\nu; \mu)$ of $\nu$ with respect to $\mu$. More explicitly we show in Section 3 that for open subsets $A$ of $\mathcal{M}(\Omega)$

$$\lim_{n} \frac{1}{n^d} \log \mu[\rho_{V_n} eA] \geq - \inf_{\nu \in A \cap \mathcal{M}_S(\Omega)} h(\nu; \mu),$$

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and in Section 4 it is shown that for closed subsets $A$ of $\mathcal{M}(\Omega)$

$$\lim_{n \to \infty} \frac{1}{n^d} \log \mu[\rho^\nu_n \in A] \leq -\inf_{\nu \in A} h(\nu; \mu).$$

By the contraction principle [V], [S], we obtain in particular a large deviation principle for the empirical distributions

$$R^V_n(\omega) = \frac{1}{n^d} \sum_{i \in \mathcal{V}_n} \delta_\omega(i)$$

on the state space $S$. In Section 5 we provide a detailed description of the resulting rate function.

For background on large deviations we recommend [V] and [S], but no prior knowledge of the subject will be assumed. The pioneering paper on large deviations for the empirical process of a Markov process is [DV(a)], and our indebtedness to this work will be clear.

After this work was completed we received preprints by S. Olla and F. Comets in which results very similar to theorems 3.1 and 4.1 are given; the method of proof of these authors is completely different from ours.

2. PRELIMINARIES

The purpose of this section is to introduce notation, summarize some known results which will be needed below, and derive some preliminary results. The reader may choose to skim this section and refer back to it as needed.

When working with a fixed space $X$ we write $X^C = X - Y$ for any subset $Y$ of $X$. If $X$ is a compact metric space, $C(X)$ denotes the class of continuous functions from $X$ to the reals, and $\mathcal{M}(X)$ is the class of probability measures on the Borel sets of $X$, topologized by weak convergence.

We will be concerned with the $d$-dimensional lattice $\mathbb{Z}^d$, a fixed finite set $S$, and the space $\Omega$ of all configurations $\omega: \mathbb{Z}^d \to S$ topologized by the compact product topology. For each $i \in \mathbb{Z}^d$ the shift map $\theta_i: \Omega \to \Omega$ is defined by $(\theta_i \omega)(k) = \omega(k + i)$, $k \in \mathbb{Z}^d$. Let $\mathcal{M}_S(\Omega)$ denote the class of all
\( \mu \in \mathcal{M}(\Omega) \) which are stationary in the sense that \( \mu = \mu \circ \theta^{-1} \) for all \( i \in \mathbb{Z}^d \).

For any positive integer \( n \), let \( V_n \) be the cube of all \( t = (t_1, \ldots, t_d) \in \mathbb{Z}^d \) with all coordinates non-negative and strictly less than \( n \). For \( s \in \mathbb{Z}^d \) and \( t \in \mathbb{Z}^d \) the distance between \( s \) and \( t \) is the sum of the absolute values of differences between the components. For \( V \subseteq \mathbb{Z}^d \) and \( p \) a positive integer, \( V_p \) is to denote the set of \( t \in V_c \) whose distance from \( V \) is at most \( p \). Let \( N_p(0) \) be the set of all \( t \in \mathbb{Z}^d \) whose distance from \( 0 \) is at most \( p \).

For \( V \subseteq \mathbb{Z}^d \) we denote by \( \mathcal{F}_V \) the \( \sigma \)-field on \( \Omega \) generated by the projections \( \omega + \omega(t) \), \( t \in V \), and by \( \omega_V \) the restriction of \( \omega \in \Omega \) to \( V \). Let \( U \) denote the class of finite subsets of \( \mathbb{Z}^d \). For \( \mu \in \mathcal{M}(\Omega) \) and \( V \in U \) we denote by \( \mu_V \) the marginal distribution of \( \mu \) on \( S^V \), by \( \mu^*_V(\cdot|n) \) the regular conditional distribution on \( \mathcal{F}_{S^d} \) given \( \mathcal{F}_{V_c} \) at the point \( n \in \Omega \), and by \( \mu_V(\cdot|n) \) its marginal distribution on \( S^V \). Also, if \( p \) is a positive integer, \( \mu^*_{V,p}(\cdot|n) \) or \( \mu_{V,p}(\cdot|n) \) denotes the conditional distribution given \( \mathcal{F}_{V_p} \) on \( \mathcal{F}_{S^d} \). An interaction potential is a collection of maps \( U(V,\cdot) : S^V \rightarrow \mathbb{R}, V \in U \). It is stationary if

\[
(2.1) \quad U(V,\omega_V) = U(V + t, (\theta_t^{-1} \omega)_{V+t}).
\]

Henceforth \( U \) will denote a fixed stationary interaction potential which also satisfies the condition

\[
(2.2) \quad \sum_{0 \in V \in U} \|U(V,\cdot)\| < \infty
\]

where the norm is the supremum norm. A measure \( \mu \in \mathcal{M}(\Omega) \) is a Gibbs measure with respect to \( U \) if \( \mu_V(\cdot|n) \) can be chosen as

\[
(2.3) \quad \mu_V(\omega_V|n) = (Z_V(n))^{-1} \exp(-E_U(\omega_V|n))
\]
where

\[(2.4)\quad E_V(\omega_V | \eta) := \sum_{A: A \cap V \neq \emptyset} U(A, \xi_A)\]

with \(\xi(i) := \omega(i)\) for \(i \in V\) and \(\xi(i) := \eta(i)\) for \(i \in V^c\), and

\[(2.5)\quad Z_V(\eta) := \sum_{\xi \in \mathcal{S}} \exp(-E_V(\xi | \eta)).\]

\(\mu\) is called a Markov random field if (2.3) only depends on \(\eta_{\partial V}\), and this means that \(U\) is a nearest neighbor potential, i.e., \(U(A, \cdot) \equiv 0\) whenever \(A\) contains two points the distance between which exceeds one; see [P]. We define \(\mathcal{G}(U)\) as the class of all Gibbs measures with respect to the interaction potential \(U\). Then

\[(2.6)\quad \mathcal{G}(U) \supseteq (U) \cap \mathcal{M}_s(\Omega) \neq \emptyset;\]

see [P] Theorem 4.3.

Let us now introduce some thermodynamical quantities and recall the corresponding limit theorems; see [F] for proofs. For \(\nu \in \mathcal{M}_s(\Omega)\) and \(V \in \mathcal{V}\), we denote by

\[H_V(\nu) := -\sum_{\xi \in \mathcal{S}} \nu_V(\xi) \log \nu_V(\xi)\]

the entropy of \(\nu_V\). The specific entropy of \(\nu\) is defined as

\[(2.7)\quad h(\nu) := \lim_{n} \frac{1}{|V_n|} H_V(\nu),\]

where \(|V_n|\) denotes the cardinality of \(V_n\). More precisely, the d-dimensional Shannon-McMillan theorem holds:

\[(2.8)\quad \lim_{n} \frac{1}{|V_n|} \log \nu_{V_n}(\omega_V)\]

exists in \(L^1(\nu)\) (see [F], Theorem 2.4), and even \(\nu\) - a.s. (see [F] (4.28) for
a Gibbs measure \( \nu \) and \([\Omega W]\) for a general \( \nu \in \mathcal{M}_s(\Omega) \). The specific energy of \( \nu \) is defined by

\[
\epsilon_\Omega(\nu) := \lim_{n} \frac{1}{|V_n|} \int \mathcal{E}_{V_n} (\omega_{V_n} | \eta) \nu(d\eta)
\]

where the limit does not depend on \( \eta \in \Omega \). More precisely, for any sequence \( \eta_n \in \Omega \) the limit

\[
\lim_{n} \frac{1}{|V_n|} \mathcal{E}_{V_n} (\omega_{V_n} | \eta_n)
\]

exists \( \nu\text{-a.s.} \) and in \( L^1(\nu) \) and coincides with the conditional expectation of

\[
\sum_{0 \in V \in \mathcal{V}} \frac{U(V, \omega_V)}{|V|}
\]

with respect to the \( \sigma \)-algebra of shift-invariant events. In particular,

\[
\epsilon_\Omega(\nu) = \int \sum_{0 \in V \in \mathcal{V}} \frac{U(V, \omega_V)}{|V|} \nu(d\omega),
\]

and this shows, due to (2.2), that \( \epsilon_\Omega \) is a continuous functional on \( \mathcal{M}_s(\Omega) \). The proof of (2.10) uses the relation

\[
\lim_{n} \frac{1}{|V_n|} \sup_{\omega, \eta, \eta'} |\mathcal{E}_{V_n} (\omega_{V_n} | \eta) - \mathcal{E}_{V_n} (\omega_{V_n} | \eta')| = 0,
\]

and this will be needed below; see (4.16) in [F].

Also the pressure defined by

\[
p_\Omega := \lim_{n} \frac{1}{|V_n|} \log Z_{V_n} (\eta)
\]

exists and is independent of \( \eta \in \Omega \).

Now take \( \mu \in \Omega \setminus \Omega_s(\Omega) \) and \( \nu \in \mathcal{M}_s(\Omega) \). Then

\[
H_V(\nu; \mu) := \sum_{\xi \in S} \nu_V(\xi) \log \frac{\nu_V(\xi)}{\mu_V(\xi)} > 0
\]
defines the relative entropy of \( \nu \) with respect to \( \mu \), and the specific relative entropy is given by

\[
(2.15) \quad h(\nu;\mu) = \lim_{n} \frac{1}{|V_n|} H_{V_n}(\nu;\mu).
\]

The limit in (2.15) exists, and it satisfies the following variational principle:

\[
(2.16) \quad h(\nu;\mu) = e_U(\nu) - h(\nu) + p_U > 0,
\]

and the last inequality becomes an equality if and only if \( \nu \in \mathcal{G}(U) \); see [F] (4.25), (4.27). Since \( e_U \) is continuous and \( h \) is upper semi-continuous, (2.16) shows that \( h(\nu;\mu) \) is a lower semi-continuous function on \( \mathcal{U}_\mathcal{S}(\Omega) \).

We shall need the fact that for \( \nu \in \mathcal{U}_\mathcal{S}(\Omega) \)

\[
(2.17) \quad \lim_{n} \frac{1}{|V_n|} \log \frac{\nu_n(\omega_n)}{\mu_n(\omega_n)}
\]

exists in \( L^1(\nu) \), and that this limit coincides with \( h(\nu;\mu) \) \( \nu \)-a.e. if \( \nu \) is ergodic. To see this, observe that by (2.12)

\[
\lim_{n} \frac{1}{|V_n|} \log \frac{\mu_n(\omega_n)}{\nu_n(\omega_n | \eta)} = 0
\]

for any \( \eta \in \Omega \); see [F] (4.22). So the limit in (2.17) may be written as

\[
(2.18) \quad \lim_{n} \frac{1}{|V_n|} \log \frac{\nu_n(\omega_n)}{\mu_n(\omega_n | \eta)} = \lim_{n} \frac{1}{|V_n|} \log \nu_n(\omega_n) + p_U + \lim_{n} \frac{1}{|V_n|} \log E_n(\omega_n | \eta).
\]

The assertion involving (2.17) is now justified by (2.8) and (2.10), and the convergence holds in fact \( \nu \)-a.e.
For a positive integer $p$ we introduce

$$\gamma_p = \sum_{A \in \Omega, A \neq N_p(0)} \# U(A, \cdot) \|.$$  \hspace{1cm} (2.19)

**2.1 Lemma.** Let $\eta \in \Omega$ and $\eta' \in \Omega$ coincide on $\bar{\alpha}_p V$. Then

$$\frac{\mu_V(\omega_V | \eta)}{\mu_V(\omega_V | \eta')} < 4|V|\gamma_p, \quad \omega_V \in \mathcal{S}_V.$$  \hspace{1cm} (2.20)

**Proof:** In (2.4) break the summation into two parts, $\hat{\Sigma} = \hat{\Sigma}' + \hat{\Sigma}''$ where the first sum is over those $A$ included in $V \cup \bar{\alpha}_p V$, while the second sum is over those $A$ intersecting $(V \cup \bar{\alpha}_p V)^c$. Then

$$\sum_{i \in V} A \ni i, A \cap (V \cup \bar{\alpha}_p V)^c \neq \emptyset \quad \# U(A, \cdot) \| = |V|\gamma_p.$$

So we obtain

$$|E_V(\omega_V | \eta) - E_V(\omega_V | \eta')| < 2|V|\gamma_p$$

and

$$Z_V(\eta) > \sum_{\xi \in \mathcal{S}_V} \exp(-E_V(\xi | \eta') - 2|V|\gamma_p)$$

$$= Z_V(\eta') e^{-2|V|\gamma_p}.$$

Hence

$$\frac{\mu_V(\omega | \eta)}{\mu_V(\omega | \eta')} = \frac{Z_V(\eta') - |E_V(\omega_V | \eta) - E_V(\omega_V | \eta')|}{Z_V(\eta)} e^{2|V|\gamma_p}$$

$$< e^{4|V|\gamma_p}.$$

We need a remark on the space $\mathcal{M}(\eta)$. $\mathcal{M}(\eta)$ can be viewed as a compact metric space, and we shall use the following explicit metric. Choose a sequence
(\phi_n) of continuous functions on \( \Omega \) satisfying the following conditions: (i) the span of \( (\phi_n) \) is dense in \( C(\Omega) \); (ii) \( \| \phi_n \| < 1, \ n = 1, 2, \ldots \); (iii) for each \( n \) there exists \( V \in \mathcal{V} \) so that \( \phi_n \) is \( \nu \)-measurable. Now define

\begin{equation}
(2.21) \quad \text{dist}(\nu, \mu) = \sum_{n=1}^{\infty} 2^{-n} |\int \phi_n d\nu - \int \phi_n d\mu| 
\end{equation}

for \( \nu, \mu \in \mathcal{M}(\Omega) \).

3. LOWER BOUND

The following theorem will be proved in this section.

3.1 **THEOREM.** Let \( \mu \in \mathcal{U}(U) \cap \mathcal{M}_s(\Omega) \) where \( U \) is a stationary interaction potential satisfying (2.4). Then for any open subset \( G \) of \( \mathcal{M}(\Omega) \)

\begin{equation}
(3.1) \quad \lim_{n \to \infty} \frac{1}{|V_n|} \log \mu(\rho_{V_n} \in G) \geq -\inf_{\nu \in G \cap \mathcal{M}_s(\Omega)} h(\nu; \mu).
\end{equation}

The proof will use Lemma 3.2. A more general lemma (for \( d = 1 \)) was given in [0], but it will be convenient to have a direct proof.

3.2 **LEMMA.** Let \( \nu \in \mathcal{M}_s(\Omega) \). Then there exists a sequence \( (\nu_n) \) of ergodic measures converging to \( \nu \) such that

\begin{equation}
(8.2) \quad \lim_{n \to \infty} h(\nu_n) = h(\nu).
\end{equation}

**PROOF.** For \( n > 1 \) denote by \( \tilde{\nu}_n \) the measure which coincides with \( \nu \) on each \( \sigma \)-field \( \mathcal{V}_{n+k} \), \( k \in \mathbb{Z}^d \), and makes these \( \sigma \)-field independent. The measure
\[ \nu_n := \frac{1}{|V_n|} \sum_{i \in V_n} \tilde{\nu}_n \circ \theta_i^{-1} \]

is stationary. To show that \( \nu_n \) is ergodic let \( B \) be an invariant event, that is \( \theta_i B = B \) for all \( i \in \mathbb{Z}^d \). It is easily seen that each \( \nu_n \circ \theta_i^{-1} \) satisfies the Kolmogorov zero-one law, and so \( \nu \circ \theta_i^{-1}(B) := b_i \in \{0,1\} \). Also, for \( i \) and \( k \in \mathbb{Z}^d \), \( \nu \circ \theta_{i+k}^{-1}(B) = \nu \circ \theta_k^{-1}(\theta_i^{-1}B) = \nu \circ \theta_k^{-1}(B) \), so that \( b_{i+k} = b_i \), and so \( b_i = b \) does not depend on \( i \). By the definition of \( \nu_n \), \( \nu_n(B) = b \).

It is easy to check that the measures \( \nu_n \) converge weakly to \( \nu \). Since the specific entropy \( h(\cdot) \) is upper semi-continuous it follows that

\[ \limsup_{n} h(\nu_n) < h(\nu). \]

For fixed \( i \in V_n \), the cube \( V_{n+i} \) contains at least \((N-1)^d\) disjoint boxes of the form \( V_n + i + n \cdot k \) with \( k \in \mathbb{Z}^d \), and on each such cube the entropy of \( \theta_i \tilde{\nu}_n \) is given by \( H_{V_n}(\nu) \); (here \( \theta_i \tilde{\nu}_n := \tilde{\nu}_n \circ \theta_i^{-1} \)). Thus

\[ H_{V_n}(\theta_i \tilde{\nu}_n) > (N - 1)^d H_{V_n}(\nu). \]

By Jensen's inequality

\[ H_{V_{N+n}}(\nu) > \frac{1}{|V_n|} \sum_{i \in V_n} H_{V_{N+n}}(\theta_i \tilde{\nu}_n) > (N - 1)^d H_{V_n}(\nu) \]

hence

\[ \frac{1}{|V_{N+n}|} H_{V_{N+n}}(\nu) > \left( \frac{N - 1}{N} \right)^d \cdot \frac{1}{|V_n|} H_{V_n}(\nu). \]

Letting \( N \to \infty \) we obtain

\[ h(\nu) > \frac{1}{|V_n|} H_{V_n}(\nu) \]

and this implies

\[ \lim_{n} h(\nu_n) > h(\nu). \]
3.3 **Proof of Theorem 3.1.** 1) Let $\nu \in \mathcal{W}(\Omega)$ and $G$ an open neighborhood of $\nu$. It will suffice to show

\begin{equation}
\lim_{n} \frac{1}{|V_n|} \log \mu[\rho_{V_n} \in G] > -h(\nu; \mu)
\end{equation}

(3.3)

2) Assume now that $\nu$ is ergodic, $G$ a neighborhood of $\nu$. In view of (2.24), there is a neighborhood

$$G_0 = \bigcap_{k=1}^{n} \{ \nu' | \int f_k d\nu' - \int f_k d\nu | < \varepsilon \} \subseteq G$$

of $\nu$, where $f_1, \ldots, f_n$ are $\mathcal{F}_{N_p(0)}$-measurable for some $p > 1$. Since $\nu$-a.s. $\rho_{V_n}$ converges weakly to $\nu$,

$$\lim_{n} \mu[\rho_{V_n} \in G_0] = 1.$$

Assume $h(\nu; \mu) < \infty$, as otherwise there is nothing to prove. Let $W_n := \nu_n \circ \rho_{V_n}$. Then $\nu$ restricted to $\mathcal{F}_{W_n}$ is absolutely continuous with respect to $\mu$ restricted to $\mathcal{F}_{W_n}$; denote the corresponding Radon-Nikodym derivative by $\phi_{W_n}$, so that

$$\lim_{n} \frac{1}{|V_n|} \log \phi_{W_n} = \lim_{n} \frac{1}{|W_n|} \log \phi_{W_n}$$

$$= h(\nu; \mu) \text{ in } L^1(\nu)$$

by (2.17). Now note that the set

$$\{ \rho_{V_n} \in G_0 \} = \bigcap_{k=1}^{n} \{ | \frac{1}{|V_n|} \sum_{i \in V_n} f_k \circ \theta_i - \int f_k d\nu | < \varepsilon \}$$

belongs to $\mathcal{F}_{W_n}$. This allows us to write

$$\mu[\rho_{V_n} \in G] > \mu[\rho_{V_n} \in G, \frac{1}{|V_n|} \log \phi_{W_n} < h(\nu; \mu) + \varepsilon; \phi_{W_n} > 0]$$

$$> e^{-\frac{1}{|V_n|} (h(\nu; \mu) + \varepsilon)} \mu[\rho_{V_n} \in G_0, \frac{1}{|V_n|} \log \phi_{W_n} < h(\nu; \mu) + \varepsilon]$$
and since the second factor in the last number approaches one by (2.17) we obtain (3.3).

3) Now let \( \nu \in \mathcal{M}_s(\Omega) \), \( G \) a neighborhood of \( \nu \). Approximate \( \nu \) by ergodic \( \nu_n \) with \( h(\nu_n) + h(\nu) \) as ensured by Lemma 3.2. Then the left side of (3.3) is greater or equal to \( -h(\nu_n; \mu) \) for all big enough \( n \). Remembering (2.16) and the fact that \( e(\cdot) \) is continuous, we see that \( h(\nu_n; \mu) + h(\nu; \mu) \), and (3.3) follows. \( \square \)

4. UPPER BOUND

In this section we prove

4.1 Theorem. Let \( \mu \in \mathcal{G}(U) \cap \mathcal{M}_s(\Omega) \). Then for any closed subset \( A \) of \( \mathcal{M}(\Omega) \)

\[
\lim_{n \to \infty} \frac{1}{|V_n|} \log \left[ \rho_{V_n} \in A \right] \leq \inf_{\nu \in A \cap \mathcal{M}_s(\Omega)} h(\nu; \mu)
\]

(\( \inf \phi = \infty \)).

Before we can prove the theorem we need some definitions and several lemmas. In the remainder of this section \( \mu \in \mathcal{G}(U) \cap \mathcal{M}_s(\Omega) \).

For \( \nu \in M_s(\Omega) \) we introduce

\[
(4.1) \quad H_{V,\rho}(\nu; \mu) = \int H(v_{V,\rho}(\cdot | \eta); u_{V,\rho}(\cdot | \eta)) \nu(d\eta)
\]

\[
= H_{V \cup \mathcal{V}}(\nu; \mu) - H_{\mathcal{V}}(\nu; \mu).
\]

Next let \( C_{V,\rho} \) denote the class of all \( \mathcal{V} \cup \mathcal{V}_{\rho} \)-measurable functions on \( \Omega \) which satisfy

\[
(4.2) \quad \int e^{\phi_\mu V_{V,\rho}}(\cdot | \eta) < 1, \quad \eta \in \Omega
\]
and also

\[ (4.3) \quad \phi < |V| \log \alpha^{-1} \]

where \( \alpha := \inf_{s \in S, n \in \Omega} \mu_{\{i\}}(s|n) > 0 \)

**4.2 Lemma.** \( H_{V,p}(\nu;\mu) = \sup_{\phi \in C_{V,p}} \int \phi \, d\nu. \)

**Proof:** For \( \phi \in C_{V,p}, n \in \Omega, \) let

\[ d_{\lambda} = \left( \int e^{\phi d_{\nu_{V,p}}^*(\cdot|n)} \right)^{-1} e^{\phi d_{\nu_{V,p}}^*(\cdot|n)} \cdot \]

Condition (4.2) and the fact that relative entropy is non-negative give

\[ H(\nu_{V,p}(\cdot|n); \mu_{V,p}(\cdot|n)) = H(\nu_{V,p}(\cdot|n); \lambda_V) \]

\[ + \int \phi d_{\nu_{V,p}}^*(\cdot|n) - \log \int e^{\phi d_{\nu_{V,p}}^*(\cdot|n)} \]

\[ > \int \phi d_{\nu_{V,p}}^*(\cdot|n) \]

and hence

\[ (4.4) \quad H_{V,p}(\nu;\mu) > \int \phi \, d\nu. \]

Now define

\[ \psi(\omega) = \frac{\nu_{V,p}(\omega|\omega)}{\mu_{V,p}(\omega|\omega)} < \frac{1}{\alpha|V|}. \]

For \( c \in (0, \alpha^{-1}|V|) \) define

\[ \psi_c = (\psi \circ c)(\int \psi \circ c \, d\nu_{V,p}^*(\cdot|n))^{-1} \]

and note that \( \phi_c := \log \psi_c \) belongs to \( C_{V,p} \). By monotone convergence
\[
\lim_{c \to 0} \int \phi_c \, d\nu = \lim_{c \to 0} \int \log(\psi \circ \nu \circ c) \, d\nu - \lim_{c \to 0} \int \log[\psi \circ \nu \circ c \, d\nu] \, d\nu
\]
\[
= \int \log \psi \, d\nu = H_{V, p}(\nu; \mu).
\]

4.3 Lemma. Let \( p_n \) (\( n = 1, 2, \ldots \)) satisfy \( \lim_{n} |p_n| |V_n|^{-1} = 0 \). Then
\[
(4.6) \quad h(\nu; \mu) = \lim_{n} \frac{1}{|V_n|} H_{V_n, p_n}(\nu; \mu).
\]

Proof. Note
\[
H(\nu_{V, p}(\cdot | n); \nu_{V, p}(\cdot | n)) = H_{V}(\nu_{V, p}(\cdot | n)) - \int \log \nu_{V, p}(\cdot | n) \, d\nu_{V, p}(\cdot | n)
\]
and by (2.12)
\[
- \lim_{n} \frac{1}{|V_n|} \int \log \nu_{V, p}(\cdot | n) \, d\nu = e_U(\nu) + p_U
\]
and so, remembering (2.16) it suffices to show
\[
\lim_{n} \frac{1}{|V_n|} \int H_{V_n}(\nu_{V, p}(\cdot | n) \, d\nu = h(\gamma).
\]
But this follows from
\[
\int H_{V}(\nu_{V, p}(\cdot | n)) \, d\nu = H_{V} \circ p_V(\nu) - H_{p} \circ V(\nu)
\]
and the assumption on \( (p_n) \), since \( H_{p} \circ V(\nu) < |p| \log |S| \).

In order to obtain our upper bound we follow [DV] and introduce a stationary modification of the empirical field \( p_V \). For each non-negative integer \( n \) define \( \pi_n: \Omega + \Omega \) by
\[
\pi_n(\omega)(i + n \cdot t) = \omega(i), \quad i \in V_n, \quad t \in \mathbb{Z}^d.
\]
Now let

\[ \rho_{V_n}^S = \rho_{V_n} \circ \pi_n \]

Clearly \( \rho_{V_n}^S \in \mathcal{M}_S(\Omega) \).

4.4 Lemma. Let \( \phi: \Omega \to \mathbb{R} \) be measurable with respect to \( \mathcal{F}_{N_m}(0) \). Then

\[
|\int \phi \rho_{V_n}^S - \int \phi \rho_{V_n}^V| < \frac{|V_n| - |V_n - 2m|}{|V_n|} 2\|\phi\|
\]

where \( \|\phi\| \) denotes the supremum norm of \( \phi \).

Proof: Note that

\[
\int \phi \rho_{V_n}^S = \frac{1}{|V_n|} \sum_{i \in V_n} \phi \circ \theta_i \circ \pi_{V_n}
\]

and

\[
\int \phi \rho_{V_n}^V = \frac{1}{|V_n|} \sum_{i \in V_n} \phi \circ \theta_i
\]

and that the summands on the right side agree except for those \( i \in V_n \) which satisfy \( i + N_m(0) \subset V_n \).

4.5 Lemma. For \( k, p > 1, n > k + p, \phi \in C_{V_n, p} \) and any measurable subset \( A \) of \( \mathcal{M}_S(\Omega) \)

\[
\frac{1}{|V_n|} \log \nu[\rho_{V_n}^S \in A] < - \inf_{V_k} \frac{1}{|V_k|} \int \phi d\nu +
\]

\[
+ \frac{|V_n - V_n - 2m - 2p|}{|V_n|} \cdot 2\|\phi\| + [1 - \left(\frac{k}{k+p} - \frac{k}{n}\right)^d] \log \alpha^{-1} + 4 \frac{|V_n + k|}{|V_k|} \gamma_p.
\]

Proof: For \( n \) large, decompose \( V_n \) into a family of blocks \( B_j = V_k + j \) and separating corridors, arranged so that each block \( B_j \) is separated from each of its neighbors by a corridor of width \( p \). Let \( W_{n,k,p} \) be the set of points in \( V_n \) belonging to one of the blocks \( B_j \). Let

\[ \psi_i = \sum_{t \in K_i} \phi \circ \theta_t, \quad i \in V_k \]
above $R_i$ is the set of $t \in V_n$ such that $t = i + j$ for some $j$
corresponding to a block $B_j$ in our decomposition. Using (4.3) we obtain

\[
\frac{1}{|V_k|} \sum_{i \in V_n} \phi \circ \theta_i < |V_n - W_{n,k,p}| \log \alpha^{-1} + \frac{1}{|V_k|} \sum \psi_i
\]

By Jensen's inequality

\[
\exp\left(\frac{1}{|V_k|} \sum_{i \in V_k} \psi_i\right) \leq \frac{1}{|V_k|} \sum_{i \in V_k} \exp(\psi_i)
\]

Now

\[
\int \exp(\psi_i) d\mu = \int \exp(\sum_{t \in R_i} \phi \circ \theta_t) d\mu = \prod_{t \in R_i} \exp(\phi \circ \theta_t) d\mu
\]

and this is to be estimated by successive conditioning. For each $t \in R_i$, the
factors $\exp(\phi \circ \theta_s)$ with $s \in R_i - \{t\}$ are $\mathcal{F}_{(V_k+t)C}$-measurable. On the
other hand we obtain from Lemma 2.1

\[
E_{\mu}[\mathbf{e}^{\phi \circ \theta_t} | \mathcal{F}_{(V_k+t)C}] = \int e^{\phi_{\mu_{V_k}^*}} (d\omega \cdot \cdot) \circ \theta_t
\]

\[
\leq e^{4|V_k|^\gamma_p} \int e^{\phi_{\mu_{V_k}^*}} (d\omega \cdot \cdot) \circ \theta_t < e^{4|V_k|^\gamma_p}
\]

The cardinality of $R_i$ is at most $(\frac{n + k}{k})^d$ and so

\[
\int \psi_i d\mu \leq \exp(4(n + k)^d \gamma_p)
\]

The inequalities (4.9), (4.10), and (4.11) imply

\[
\int \exp\left(\frac{|V_n|}{|V_k|} \int \phi d\nu_n\right) d\mu \leq \exp(|V_n - W_{n,k,p}| \log \alpha^{-1} + 4|V_{n+k}| \gamma_p)
\]

The Chebychev inequality and Lemma 4.4 with $m = k + p$ imply
(4.13) \[ \mu[p^n \in A] \leq \exp(-\frac{|V_n|}{|V_k|} \inf_{\nu \in A} \int \phi \, d\nu) \cdot \exp(\frac{|V_n|}{|V_k|} \int \phi \, d\mu^S_n) d\nu \]

\[ \leq \exp(-\frac{|V_n|}{|V_k|} \inf \int \phi \, d\nu) + \frac{|V_n - V_{n-2k-2p}|}{|V_k|} \cdot \exp(\frac{|V_n|}{|V_k|} \int \phi \, d\nu) d\mu \]

The last factor is estimated by (4.12), and noting

\[ |V_n - W_{n,k,p}| \leq n^d(1 - (\frac{k}{k+p} - \frac{k}{n})^d) \]

leads to (4.8).

4.6 Proof of Theorem 4.1. 1) Let us first show that for any closed subset \( A \) of \( \mathcal{M}_s(\Omega) \)

(4.14) \[ J^S(A) := \lim_{n \to \infty} \frac{1}{|V_k|} \log \mu[p^n \in A] \leq -\inf_{\nu \in A} h(\nu; \mu) \]

Letting \( n \) approach infinity in (4.8) gives us, for \( \phi \in C_{k,p} \)

\[ J^S(A) \leq -\inf_{\nu \in A} \frac{1}{|V_k|} \int \phi \, d\nu + 4\gamma_p + (1 - (\frac{k}{k+p})^d) \log n^{-1} \]

Now choose \( p = p(k) \) so that \( p \) tends to infinity with \( k \) but \( p(k)/k \) tends to zero. Write \( C_k \) for \( C_{k,p(k)} \). For \( \epsilon > 0 \) there exists \( k_\epsilon \) such that

\[ |\gamma_{p(k)}| < \epsilon \text{ for } k > k_\epsilon \]. For \( k > k_\epsilon \), \( \phi \in C_k \)

\[ J^S(A) - \epsilon < -\inf_{\nu \in A} \frac{1}{|V_k|} \int \phi \, d\nu \]

Thus

\[ J^S(A) - \epsilon < -\sup_{k \geq k_\epsilon} \sup_{\phi \in C_k} \inf_{\nu \in A} \frac{1}{|V_k|} \int \phi \, d\nu \]

and in fact
\[(4.15) \quad J^S(A) - \varepsilon \leq \sup_{A \subseteq \bigcup A_j} \inf_{1 \leq j \leq q} \inf_{k \gg k \varepsilon} \sup_{\phi \in C_k} \sup_{\nu \in A_j} \frac{1}{|V_k|} \int_{A_j} \phi \, d\nu \]

since \( J^S(A) = \max_j J^S(A_j) \) for any finite covering \( A_1, \ldots, A_q \) of \( A \).

For any \( \nu \in A \) there exists \( k \gg k \varepsilon \) and \( \phi \in C_k \) so that

\[\frac{1}{|V_k|} \int_{A_j} \phi \, d\nu > \inf_{\nu \in A} h(\nu; \mu) - \varepsilon / 2\]

by Lemmas 4.2 and 4.3. Since \( \int_{\phi} d\nu \) is a continuous functional on \( \mathcal{U}(\Omega) \) we can conclude that

\[\frac{1}{|V_k|} \int_{A_j} \phi \, d\nu > \inf_{\nu \in A} h(\nu; \mu) - \varepsilon\]

for all \( \nu \) in some open neighborhood \( G_\nu \) of \( \nu \). Now we use the assumption that \( A \) is closed, hence compact. There exists a finite covering of \( A \) by open sets \( G_1, \ldots, G_q \) such that

\[\inf_{1 \leq j \leq q} \inf_{k \gg k \varepsilon} \sup_{\phi \in C_k} \sup_{\nu \in G_j} \frac{1}{|V_k|} \int_{A_j} \phi \, d\nu > \inf_{\nu \in A} h(\nu; \mu) - \varepsilon\]

This shows that the right side of \((4.15)\) is bounded above by \(- \inf_{\nu \in A} h(\nu; \mu) + \varepsilon \). Since \( \varepsilon \) was arbitrary this implies \((4.14)\).

2) Metrize \( \mathcal{U}(\Omega) \) as in \((2.21)\). Then by Lemma 4.4 the distance between \( \rho_{V_n}^S \) and \( \rho_{V_n}^S \) converges to zero uniformly in \( \omega \) (recall that these are random measures) as \( n \to \infty \). Hence if \( \varepsilon > 0 \) and \( A_{\varepsilon} \) is a closed \( \varepsilon \)-neighborhood of \( A \), there exists \( n_0(\varepsilon) \) such that \( n > n_0(\varepsilon) \) implies

\[\left[ \rho_{V_n}^S \in A_{\varepsilon} \right] \subseteq \left[ \rho_{V_n}^S \in A_{\varepsilon} \right] = \left[ \rho_{V_n}^S \in A_{\varepsilon} \right] \cap \mathcal{U}_s(\Omega)\]

Thus \((4.14)\) implies

\[J(A) := \lim_{n \to \infty} \frac{1}{|V_n|} \log \mu \left[ \rho_{V_n}^S \in A \right] < - \inf_{\nu \in A_{\varepsilon} \cap \mathcal{U}_s(\Omega)} h(\nu; \mu)\]
Now let \( \epsilon \downarrow 0 \) and use the fact that \( h(\nu;\mu) \) is a lower semi-continuous function of \( \nu \) to obtain Theorem 4.1.

5. LARGE DEVIATIONS FOR THE EMPIRICAL DISTRIBUTION

Let \( \mu \in \mathcal{M}(\Omega) \cap \mathcal{G}(U) \) be a stationary Gibbs measure with interaction potential \( U \). In the language of \([V]\) we have shown that the sequence of measures \( \mu \circ R_{V_n}^{-1} \) on \( \mathcal{M}(\Omega) \) satisfies the large deviation principle with rate function

\[
I(\nu) = \begin{cases} 
  h(\nu;\mu) & \nu \in \mathcal{M}_S(\Omega) \\
  \infty & \text{otherwise}
\end{cases}
\]

One important consequence is Varadhan's abstraction of the Laplace method: For any \( \phi \in C(\Omega) \)

\[
p(\phi;\mu) := \lim_{n \to \infty} \frac{1}{|V_n|} \log \int \exp(\sum_{i \in V_n} \phi \circ \theta_i) d\mu
\]

exists and satisfies

\[
p(\phi;\mu) = \sup_{\nu \in \mathcal{M}(\Omega)} [\int \nu d\mu - I(\nu)]
\]

as shown in \([V]\) Theorem 2.2. By convex duality (5.2) implies

\[
h(\nu;\mu) = \sup_{\phi \in C(\Omega)} [\int \phi d\nu - p(\phi;\mu)]
\]

for any \( \nu \in \mathcal{M}_S(\Omega) \). This follows, e.g., from \([S]\) Theorem 7.15, if we use the natural embedding of \( \mathcal{M}(\Omega) \) into the topological vector space of signed measures on \( \Omega \).
Let us now consider large deviations for the empirical distribution

\[ R_{V_n}(\omega) := \frac{1}{|V_n|} \sum_{i \in V_n} \delta_{\omega(i)} \in \mathcal{M}(S). \]

Let \( \pi : \mathcal{M}(\Omega) \to \mathcal{M}(S) \) associate with each \( \nu \in \mathcal{M}(\Omega) \) its marginal distribution \( \nu_0 = \pi(\nu) \) at the origin \( 0 \in \mathbb{Z}^d \). Then

\[ R_{V_n} = \Pi(\rho_{V_n}), \]

and the contraction principle of [V] 2, Remark 1 shows that the sequence \( \mu \circ R_{V_n}^{-1}, n = 1, 2, \ldots \) satisfies the large deviation principle with rate function

\[ (5.4) \quad I_0(Q) = \inf_{\nu \in \mathcal{M}(\Omega): \pi(\nu) = Q} I(\nu) = \inf_{\nu \in \mathcal{M}_S(\Omega): \pi(\nu) = Q} \inf \{ h(\nu; \mu) \} \]

More explicitly,

\[ (5.5) \quad \lim_{n \to \infty} \frac{1}{|V_n|} \log \mu[R_{V_n} \in A] = \inf_{Q \in A} I_0(Q) \]

for any open set \( A \subseteq \mathcal{M}(S) \), and

\[ (5.6) \quad \lim_{n \to \infty} \frac{1}{|V_n|} \log \mu[R_{V_n} \in A] \leq \inf_{Q \in A} I_0(Q) \]

for any closed set \( A \subseteq \mathcal{M}(S) \). Since \( h(\cdot; \mu) \) is lower semicontinuous the infimum in (5.5) is actually attained. In Theorem (5.5) the class of minimizing measures \( \nu \in \mathcal{M}_S(\Omega) \) is shown to coincide with \( G(U^f) \), where \( U^f \) is a generalized interaction potential obtained from \( U \) and some function \( f \) on \( S \) which depends on \( Q \).

Let us first note that, again by Laplace's method [V], the limit

\[ P_0(f; \mu) := \lim_{n \to \infty} \frac{1}{|V_n|} \log \exp \left( \sum_{i \in V_n} f(\omega(i)) \right) d\mu. \]
exists for any real-valued function \( f \) on \( S \) and satisfies the relations

\[
(5.7) \quad p_0(f; \mu) = \sup_{Q \in \mathcal{H}_S} [\int_\mathbb{R} dQ - I_0(Q)]
\]

and

\[
(5.8) \quad I_0(Q) = \sup_{f: S \rightarrow \mathbb{R}} [\int_\mathbb{R} dQ - p_0(f; \mu)]
\]

For our purposes, we will have to consider functions \( f \) on \( S \) which may assume the value \(-\infty\).

Let \( f: S \rightarrow [-\infty, \infty) \) be a function not identically equal to \(-\infty\). Define \( U^f \) by \( U^f(V, \omega) = U(V, \omega) \) for \(|V| > 1 \) and

\[
U^f(\{i\}, \omega) = U(\{i\}, \omega) - f(\omega(i)), \quad i \in \mathbb{Z}^d.
\]

The corresponding class of Gibbs measures \( \mathcal{G}(U^f) \) will consist of probability measure \( \mu^f \) such that for \( V \in \mathcal{V} \) and \( n \in \mathcal{W} \), a conditional distribution on \( S^V \) given \( \mathcal{F}_{Vc} \) is given by

\[
(5.9) \quad \mu^f(\omega_V | n) = (z^f_V(n))^{-1} \exp \left[ \sum_{i \in V} f(\omega(i)) \right] \mu_V(\omega_V | n)
\]

where

\[
(5.10) \quad z^f_V(n) = \sum_{\xi \in S^V} \exp \left[ \sum_{i \in V} f(\xi(i)) \right] \mu_V(\xi | n).
\]

Again \( \mathcal{H}_S(\mathcal{W}) \cap \mathcal{G}(U^f) \neq \emptyset \); see [P], Theorem 4.3. Observe that for \( \mu^f \in \mathcal{G}(U^f) \) the marginal distribution \( \mu^f_0 = \pi(\mu^f) \) is concentrated on the set

\[
S_f = \{ s \in S : f(s) > -\infty \}
\]

since
\[
\mu_f(S^c) = \sum_{s \in S^c} \int_{\mu_f(0)}(s \mid n) \mu_f(dn) = 0.
\]

5.1 Lemma. Let \( f : S \to [-\infty, \infty), f \neq -\infty \). The limit

\[
\rho_0(f; \mu) := \lim_{n \to \infty} \frac{1}{|V_n|} \int_{\log e}^{\infty} f(i) \mu(d\nu) \in [-\infty, \infty)
\]

exists and satisfies the equation

\[
\rho_0(f; \mu) = \int f d\mu_f - h(\mu_f; \mu)
\]

for any \( \mu_f \in (U_f)_{S_f} \). For \( \nu \in \mathcal{U}_S(\Omega) \) such that \( Q := \pi(\nu) \) is concentrated on \( S_f \) and \( \mu_f \in (U_f)_{S_f} \)

\[
h(\nu; \mu) = h(\nu; \mu_f) + \int f dQ - \rho_0(f; \mu)
\]

so that \( h(\nu; \mu) < \infty \) implies \( \rho_0(f; \mu) > -\infty \).

Proof: 1) From (5.10) and the relation (2.12) we obtain

\[
\lim \sup_{n} \frac{1}{|V_n|} \frac{\mu_f(\xi \mid n)}{\nu(\xi \mid n', n') = \lim \sup_{n} \log \frac{Z_f(n)}{Z_f(n')} = 0}
\]

2) Let \( \nu \in \mathcal{U}_S(\Omega) \), and assume \( Q := \pi(\nu) \) satisfies \( Q(S_f) = 1 \). Then \( \nu_f \) is concentrated on the \( \xi \in S_f \) with \( \mu_f(\xi) > 0 \). Thus we can write

\[
H_v(\nu; \mu_f) = H(\nu_f; \mu_f(\cdot \mid n)) + \int \log \frac{\mu_f(\cdot \mid n)}{\mu_f(\cdot \mid n)} \nu(d\omega)
\]

\[
= \log Z_f(n) - |V|/f dQ + H(\nu_f; \mu_f(\cdot \mid n))
\]

\[
+ \int \log \frac{\mu_f(\cdot \mid n)}{\mu_f(\cdot \mid n)} \nu(d\omega)
\]
and (5.14) implies

\[
\lim_{n} \frac{1}{|V_n|} \int \log \frac{\mu^f(\omega_V | \eta)}{\mu^f(\omega_V)} \nu(d\omega) = 0
\]

Choosing \( \nu = \mu^f \) in (5.15) the left side vanishes, and dividing by \(|V|\) and passing to the limit one obtains

\[
p^0(f; \mu) = \lim_{n} \frac{1}{|V_n|} \log Z^f\nu(\eta) = -h(\mu^f; \mu) + \int f dQ
\]

\[< \int f dQ < \infty;\]

the first equality follows from (5.14).

3) Now let \( \nu \in \mathcal{M}_s(\Omega) \) with marginal \( Q = \pi(\nu) \) satisfying \( Q(S_f) = 1 \).

Again using (5.15) and (5.16) as above leads to

\[
h(\nu; \mu^f) = p^0(f; \mu) - \int f dQ + h(\nu; \mu).
\]

\[\square\]

5.2 Theorem. Suppose \( I^0(Q) < \infty \). Then there exists a function \( f: S \rightarrow [-\infty, \infty) \) with the following properties:

(i) A measure \( \nu \in \mathcal{M}_s(\Omega) \) with marginal \( \pi(\nu) = Q \) satisfies

\[
h(\nu; \mu) = I^0(Q)
\]

if and only if \( \nu \in \mathcal{M}(U^f) \).

(ii) Both \( \int fdQ \) and \( p^0(f; \mu) \) are finite and

\[
I^0(Q) = \int fdQ - p^0(f; \mu).
\]

Proof. 1) By (5.10) we can choose a sequence \( (f_k) \) of functions on \( C(S) \) such that
(5.21) \[ I_0(Q) = \lim_{k} \left[ \int f_k dQ - P_0(f_k; \mu) \right] \]

The expression in brackets is unchanged if \( f_k \) is replaced by \( f_k + c \) for any constant \( c \). We may therefore assume

(5.22) \[ \max_{i \in S} f_k(i) = 0. \]

Going over to a subsequence if necessary we may assume

\[ f(s) := \lim_{k} f_k(s) \in [-\infty, 0] \]

exists for each \( S \), and \( f \neq -\infty \). This will be the function of whose existence is asserted by the theorem.

2) Remembering (5.22) we obtain

\[ Z^f_v(n) = \sum_{\xi \in \Gamma} \sum_{i \in S} f_k(\xi(i)) \cdot \mu_v(\xi|n) \]

\[ > \inf_{\xi \in \Gamma} \mu_v(\xi|n) > \alpha |V| \]

where \( \alpha := \inf_{s \in S, n \in \Omega} \mu_i(s|n) > 0 \). From (5.17) it follows that

\[ P_0(f_k; \mu) = \lim_{n} \frac{1}{|V_n|} \log Z^f_v(n) > \alpha. \]

This implies, due to (5.21),

(5.23) \[ \inf_{k} \int f_k dQ > -\infty, \]

and so \( Q(S_f) = 1 \).

3) Using 2) we can pass from (5.21) to

(5.24) \[ I_0(Q) = \int f dQ - \lim_{k} P_0(f_k; \mu). \]
We must still show that the last term in (5.24) agrees with \( p_0(f;\nu) \) as given in (5.11). For \( \varepsilon > 0 \) and \( k \) sufficiently big \( f_k > f - \varepsilon \), and from this one obtains at once that

\[
\lim_k p_0(f_k;\nu) > p_0(f;\nu)
\]

and hence (5.24) implies

\[
(5.25) \quad I_0(Q) < \int f \, dQ - p_0(f;\nu).
\]

On the other hand, if \( \nu \in \mathcal{M}_S \) satisfies \( \pi(\nu) = Q \) and \( h(\nu;\mu) = I_0(Q) \) then by (5.13) for \( \mu^f \in \mathcal{G}(U^f) \wedge \mathcal{M}_S \)

\[
(5.26) \quad I_0(Q) = h(\nu;\mu^f) + \int f \, dQ - p_0(f;\nu) > \int f \, dQ - p_0(f;\nu).
\]

Now from (5.25) and (5.26) follows the desired equality (5.20), and also \( h(\nu;\mu^f) = 0 \), and this implies \( \nu \in \mathcal{G}(U^f) \) by [P], Theorem 7.1

4) Suppose \( \mu^f \in \mathcal{G}(U^f) \wedge \mathcal{M}_S \) has marginal \( \pi(\mu^f) = Q \). Then \( h(\mu^f;\nu) = I_0(Q) \) follows from (5.12) and (5.20).

5.3 Remark. Let \( \mu \) be a Markov random field, and let \( Q \) be a measure on \( S \) with \( I_0(Q) < \infty \). In this case we have shown that there exists a new Markov random field of the form \( \mu^f \in \mathcal{G}(U^f) \) such that \( \mu^f \) has marginal distribution \( Q \) and satisfies

\[
I_0(Q) = h(\mu^f;\nu)
\]

This is a spatial analogue to a result of [DV], Theorem 2.1; see also [V], (13.7).
REFERENCES


