The Allen–Cahn action functional in higher dimensions

LUCA MUGNAI† AND MATTHIAS RÖGER‡
Max Planck Institute for Mathematics in the Sciences,
Inselstr. 22, D-04103 Leipzig, Germany

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The Allen–Cahn action functional is related to the probability of rare events in the stochastically perturbed Allen–Cahn equation. Formal calculations suggest a reduced action functional in the sharp interface limit. We prove the corresponding lower bound in two and three space dimensions. One difficulty is that diffuse interfaces may collapse in the limit. We therefore consider the limit of diffuse surface area measures and introduce a generalized velocity and generalized reduced action functional in a class of evolving measures.

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1. Introduction

In this paper we study the (renormalized) Allen–Cahn action functional

\[ S_\varepsilon(u) := \int_0^T \int_\Omega \left( \sqrt{\varepsilon} \partial_t u + \frac{1}{\sqrt{\varepsilon}} \left( -\varepsilon \Delta u + \frac{1}{\varepsilon} W'(u) \right) \right)^2 \, dx \, dt. \]  

(1.1)

This functional arises in the analysis of the stochastically perturbed Allen–Cahn equation [2, 20, 12, 30, 7, 9, 11] and is related to the probability of rare events such as switching between deterministically stable states.

Compared to the purely deterministic setting, stochastic perturbations add new features to the theory of phase separations, and the analysis of action functionals has drawn some attention [7, 12, 17, 18, 26]. Kohn et al. [17] considered the sharp-interface limit \( \varepsilon \to 0 \) of \( S_\varepsilon \) and identified a reduced action functional that is more easily accessible for a qualitative analysis. The sharp interface limit reveals a connection between minimizers of \( S_\varepsilon \) and mean curvature flow.

The reduced action functional in [17] is defined for phase indicator functions \( u : (0, T) \times \Omega \to \{-1, 1\} \) with the additional properties that the measure of the phase \( \{u(t, \cdot) = 1\} \) is continuous and the common boundary of the two phases \( \{u = 1\} \) and \( \{u = -1\} \) is, apart from a countable set of singular times, given as union of smoothly evolving hypersurfaces \( \Sigma := \bigcup_{t \in (0, T)} \Sigma_t \).

†E-mail: mugnai@mis.mpg.de
‡E-mail: roeger@mis.mpg.de

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reduced action functional is then defined as

\[ S^0(u) := c_0 \int_0^T \int_{\Sigma_t} |v(t, x) - H(t, x)|^2 d\mathcal{H}^{n-1}(x) \, dt + 4S_{\text{nuc}}^0(u), \tag{1.2} \]

\[ S_{\text{nuc}}^0(u) := 2c_0 \sum_i \mathcal{H}^{n-1}(\Sigma_i), \tag{1.3} \]

where \( \Sigma \) denotes the \( i \)th component of \( \Sigma \) at the time of creation, \( v \) denotes the normal velocity of the evolution \( (\Sigma_t)_{t \in (0,T)} \), \( H(t, \cdot) \) denotes the mean curvature vector of \( \Sigma_t \), and the constant \( c_0 \) is determined by \( W \),

\[ c_0 := \int_{-1}^1 \sqrt{2W(s)} \, ds. \tag{1.4} \]

(See Section 9 for a more rigorous definition of \( S^0 \).)

Several arguments suggest that \( S^0 \) describes the Gamma-limit of \( S^\varepsilon \):

- The upper bound necessary for the Gamma-convergence was formally proved [17] by the construction of good ‘recovery sequences’.
- The lower bound was proved in [17] for sequences \( (u_\varepsilon)_{\varepsilon > 0} \) such that the associated ‘energy measures’ have equipartitioned energy and single multiplicity as \( \varepsilon \to 0 \).
- In one space dimension Reznikoff and Tonegawa [26] proved that \( S^\varepsilon \) Gamma-converges to an appropriate relaxation of the one-dimensional version of \( S^0 \).

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The approach used in [17] is based on the evolution of the phases and is sensible to cancellations of phase boundaries in the sharp interface limit. Therefore in [17] a sharp lower bound is achieved only under a single-multiplicity assumption for the limit of the diffuse interfaces. As a consequence, it could not be excluded that creating multiple interfaces reduces the action.

In the present paper we prove a sharp lower bound of the functional \( S^\varepsilon \) in space dimensions \( n = 2, 3 \) without any additional restrictions on the approximate sequences.

To circumvent problems with cancellations of interfaces we analyze the evolution of the (diffuse) surface-area measures, which makes information available that is lost in the limit of phase fields. With this aim we generalize the functional \( S^0 \) to a suitable class of evolving energy measures and introduce a generalized formulation of velocity, similar to Brakke’s generalization of mean curvature flow [5].

Let us informally describe our approach and main results. Comparing the two functionals \( S^\varepsilon \) and \( S^0 \), the first and second term of the sum in the integrand (1.1) describe a ‘diffuse velocity’ and ‘diffuse mean curvature’ respectively. We will make this statement precise in (6.13) and (7.1). The mean curvature is given by the first variation of the area functional, and a lower estimate for the square integral of the diffuse mean curvature is available in a time-independent situation [28].

The velocity of the evolution of the phase boundaries is determined by the time derivative of the surface-area measures, and the nucleation term in the functional \( S^0 \) in fact describes a singular part of this time derivative.

Our first main result is a compactness result: the diffuse surface-area measures converge to an evolution of measures with a square-integrable generalized mean curvature and a square-integrable generalized velocity. In the class of such evolutions of measures we provide a generalized formulation of the reduced action functional. We prove a lower estimate that counts the propagation cost with the multiplicity of the interface. This shows that it is more expensive to move phase
boundaries with higher multiplicity. Finally we prove two statements on the Gamma-convergence (with respect to \( L^1(\Omega_T) \)) of the action functional. The first result is for evolutions in the domain of \( S^0 \) that have nucleations only at the initial time. This is in particular desirable since minimizers of \( S^0 \) are supposed to be in this class. The second result proves the Gamma-convergence in \( L^1(\Omega_T) \) under an assumption on the structure of the set of measures arising as sharp interface limits of sequences with uniformly bounded action.

We give a precise statement of our main results in Section 4. In the remainder of this introduction we describe some background and motivation.

1.1 Deterministic phase field models and sharp interface limits

Most diffuse interface models are based on the Van der Waals–Cahn–Hilliard energy

\[
E_\epsilon(u) := \int_\Omega \left( \frac{\epsilon}{2} |\nabla u|^2 + \frac{1}{\epsilon} W(u) \right) \, dx. \tag{1.5}
\]

The energy \( E_\epsilon \) favors a decomposition of \( \Omega \) into two regions (phases) where \( u \approx -1 \) and \( u \approx 1 \), separated by a transition layer (diffuse interface) of thickness of order \( \epsilon \). Modica and Mortola [22, 21] proved that \( E_\epsilon \) Gamma-converges (with respect to \( L^1 \)-convergence) to a constant multiple of the perimeter functional \( P \), restricted to phase indicator functions,

\[
E_\epsilon \to c_0 P, \quad P(u) := \begin{cases} 
\frac{1}{2} \int_\Omega |\nabla u| & \text{if } u \in BV(\Omega; \{-1, 1\}), \\
\infty & \text{otherwise}.
\end{cases}
\]

\( P \) measures the surface area of the phase boundary \( \partial^*\{u = 1\} \cap \Omega \). In this sense \( E_\epsilon \) describes a diffuse approximation of the surface-area functional.

Various tighter connections between the functionals \( E_\epsilon \) and \( P \) have been proved. We mention here just two that are important for our analysis. The (accelerated) \( L^2 \)-gradient flow of \( E_\epsilon \) is given by the Allen–Cahn equation

\[
\epsilon \partial_t u = \epsilon \Delta u - \frac{1}{\epsilon} W'(u) \tag{1.6}
\]

for phase fields in the time-space cylinder \((0, T) \times \Omega \). It is proved in different formulations [24, 8] [16] that (1.6) converges to the mean curvature flow

\[
H(t, \cdot) = v(t, \cdot) \tag{1.7}
\]

for the evolution of phase boundaries.

Another connection between the first variations of \( E_\epsilon \) and \( P \) is expressed in a (modified) conjecture of De Giorgi [6]. Considering

\[
W_\epsilon(u) := \int_\Omega \frac{1}{\epsilon} \left( -\epsilon \Delta u + \frac{1}{\epsilon} W'(u) \right)^2 \, dx \tag{1.8}
\]

the sum \( E_\epsilon + W_\epsilon \) Gamma-converges up to the constant factor \( c_0 \) to the sum of the perimeter functional and the Willmore functional \( W \),

\[
E_\epsilon + W_\epsilon \to c_0 P + c_0 W, \quad W(u) = \int_\Gamma H^2 \, d\mathcal{H}^{n-1}, \tag{1.9}
\]
where $\Gamma$ denotes the phase boundary $\partial^*\{u = 1\} \cap \Omega$. This statement was recently proved by Röger and Schätzle \cite{Roe} in space dimensions $n = 2, 3$ and is an essential ingredient to obtain the lower bound for the action functional.

### 1.2 Stochastic interpretation of the action functional

Phenomena such as the nucleation of a new phase or switching between two (local) energy minima require an energy barrier crossing and are out of the scope of deterministic models that are energy dissipative. If thermal fluctuations are taken into account such an energy barrier crossing becomes possible. In \cite{Kaw} ‘thermally activated switching’ was considered for the stochastically perturbed Allen–Cahn equation

$$\varepsilon \partial_t u = \varepsilon \Delta u - \frac{1}{\varepsilon} W'(u) + \sqrt{2\gamma} \eta_{\lambda}.$$

(1.10)

Here $\gamma > 0$ is a parameter that represents the temperature of the system, $\eta$ is a time-space white noise, and $\eta_{\lambda}$ is a spatial regularization with $\eta_{\lambda} \to \eta$ as $\lambda \to 0$. This regularization is necessary for $n \geq 2$ since the white noise is too singular to ensure well-posedness of (1.10) in higher space dimensions.

Large deviation theory and (extensions of) results by Wentzell and Freidlin \cite{Wen, Fre} yield an estimate on the probability distribution of solutions of stochastic ODEs and PDEs in the small-noise limit. This estimate is expressed in terms of a (deterministic) action functional. For instance, thermally activated switching within a time $T > 0$ is described by the set of paths

$$B := \{u(0, \cdot) = -1, \|u(t, \cdot) - 1\|_{L^\infty(\Omega)} \leq \delta \text{ for some } t \leq T\},$$

(1.11)

where $\delta > 0$ is a fixed constant. The probability of switching for solutions of (1.10) then satisfies

$$\lim_{\gamma \to 0} \gamma \ln \text{Prob}(B) = -\inf_{u \in B} S_{\varepsilon}(\lambda)(u).$$

(1.12)

Here $S_{\varepsilon}(\lambda)$ is the action functional associated to (1.10) and it converges (formally) to the action functional $S_\varepsilon$ as $\lambda \to 0$ \cite{Kaw}. Large deviation theory not only estimates the probability of rare events but also identifies the ‘most likely switching path’ as the minimizer $u$ in (1.12).

We focus here on the sharp interface limit $\varepsilon \to 0$ of the action functional $S_\varepsilon$. The small parameter $\varepsilon > 0$ corresponds to a specific diffusive scaling of the time and space domains. This choice was identified \cite{Kaw, Kaw2} as particularly interesting, exhibiting a competition between nucleation versus propagation to achieve the optimal switching. Depending on the value of $|\Omega|^{1/d}/\sqrt{T}$ a cascade of more and more complex spatial patterns is observed \cite{Kaw, Kaw2, Kaw3}. The interest in the sharp interface limit is motivated by an interest in applications where the switching time is small compared to the deterministic time scale (see for instance \cite{Kaw4}).

### 1.3 Organization

We fix some notation and assumptions in the next section. In Section 3 we introduce the concept of $L^2$-flows and generalized velocity. Our main results are stated in Section 4 and proved in Sections 5–8. We discuss some implications for the Gamma-convergence of the action functional in Section 9. Finally, in the Appendix we collect some definitions from geometric measure theory.
2. Notation and assumptions

Throughout the paper we will adopt the following notation: \( \Omega \) is an open bounded subset of \( \mathbb{R}^n \) with Lipschitz boundary; \( T > 0 \) is a real number and \( \Omega_T := (0, T) \times \Omega; x \in \Omega \) and \( t \in (0, T) \) denote the space and time variables respectively; \( \nabla \) and \( \Delta \) denote the spatial gradient and Laplacian, and \( \nabla' \) the full gradient in \( \mathbb{R} \times \mathbb{R}^n \).

We choose \( W \) to be the standard quartic double-well potential

\[
W(r) = \frac{1}{4}(1 - r^2)^2.
\]

For a family \((\mu^t)_{t \in (0, T)}\) of measures we denote by \( L^1 \otimes \mu^t \) the product measure defined by

\[
(L^1 \otimes \mu^t)(\eta) := \int_0^T \mu^t(\eta(t, \cdot)) \, dt
\]

for any \( \eta \in C^0_0(\Omega_T) \).

We next state our main assumptions.

ASSUMPTION 2.1 Let \( n = 2, 3 \) and let \((u_\epsilon^t)_{\epsilon > 0}\) be a sequence of smooth functions such that for all \( \epsilon > 0 \),

\[
S(\epsilon) \leq A_1, \quad \int_{\Omega} \left( \frac{\epsilon}{2} |\nabla u_\epsilon|^2 + \frac{1}{\epsilon} W(u_\epsilon) \right)(0, x) \, dx \leq A_2, \quad \text{(A1)}
\]

where the constants \( A_1, A_2 \) are independent of \( \epsilon > 0 \). Moreover,

\[
\nabla u_\epsilon \cdot v_{\Omega T} = 0 \quad \text{on} \quad [0, T] \times \partial \Omega. \quad \text{(A3)}
\]

REMARK 2.2 It follows from (A3) that for any \( 0 \leq t_0 \leq T \),

\[
\int_{t_0}^{b_0} \int_{\Omega_T} \left( \frac{\epsilon}{2} |\nabla u_\epsilon|^2 + \frac{1}{\epsilon} W(u_\epsilon) \right)(t_0, x) \, dx \, dt \leq A_2,
\]

By the uniform bounds (A1), (A2) this implies that

\[
\int_{\Omega_T} \frac{\epsilon}{2} |\nabla u_\epsilon|^2 + \frac{1}{\epsilon} W(u_\epsilon) \, dx \, dt \leq A_3, \quad \text{(2.1)}
\]

\[
\max_{0 \leq t \leq T} \int_{\Omega} \left( \frac{\epsilon}{2} |\nabla u_\epsilon|^2 + \frac{1}{\epsilon} W(u_\epsilon) \right)(t, x) \, dx \leq A_4, \quad \text{(2.2)}
\]

where

\[
A_3 := A_1 + 2A_2, \quad A_4 := \frac{1}{2}A_1 + A_2.
\]
Our arguments would also work for any boundary conditions for which the scalar product $\partial_t u \nabla u \cdot \nu_{\partial \Omega}$ vanishes on $\partial \Omega$, in particular for time-independent Dirichlet conditions or periodic boundary conditions.

We set
\[ w_\epsilon := -\epsilon \Delta u_\epsilon + \frac{1}{\epsilon} W'(u_\epsilon) \] (2.3)
and define for $\epsilon > 0$, $t \in (0, T)$ a Radon measure $\mu'_\epsilon$ on $\overline{\Omega}$ by
\[ \mu'_\epsilon := \left( \frac{\epsilon}{2} |\nabla u_\epsilon|^2 (t, \cdot) + \frac{1}{\epsilon} W(u_\epsilon(t, \cdot)) \right) \mathbb{L}^n, \] (2.4)
and for $\epsilon > 0$ measures $\mu_\epsilon, \alpha_\epsilon$ on $\overline{\Omega}_T$ by
\[ \mu_\epsilon := \left( \frac{\epsilon}{2} |\nabla u_\epsilon|^2 + \frac{1}{\epsilon} W(u_\epsilon) \right) \mathbb{L}^{n+1}, \] (2.5)
\[ \alpha_\epsilon := (\epsilon^1/2 \partial_t u_\epsilon + \epsilon^{-1/2} w_\epsilon)^2 \mathbb{L}^{n+1}. \] (2.6)

Restricting ourselves to a subsequence $\epsilon \to 0$ if necessary, we may assume that
\[ \mu_\epsilon \to \mu \quad \text{as Radon measures on } \overline{\Omega}_T, \] (2.7)
\[ \alpha_\epsilon \to \alpha \quad \text{as Radon measures on } \overline{\Omega}_T, \] (2.8)
for two Radon measures $\mu, \alpha$ on $\overline{\Omega}_T$, and
\[ \alpha(\overline{\Omega}_T) = \liminf_{\epsilon \to 0} \alpha_\epsilon(\Omega_T). \] (2.9)

3. $L^2$-flows

We will show that the uniform bound on the action implies the existence of a square-integrable weak mean curvature and the existence of a square-integrable generalized velocity. The formulation of weak mean curvature is standard in geometric measure theory [1, 31]. Our definition of $L^2$-flow and generalized velocity is similar to Brakke’s formulation of mean curvature flow [5].

**DEFINITION 3.1** Let $(\mu'_t)_{t \in (0, T)}$ be any family of integer rectifiable Radon measures such that $\mu := L_1 \otimes \mu'$ defines a Radon measure on $\overline{\Omega}_T$ and such that $\mu'$ has a weak mean curvature $H(t, \cdot) \in L^2(\mu')$ for almost all $t \in (0, T)$.

If there exists a positive constant $C$ and a vector field $v \in L^2(\mu, \mathbb{R}^n)$ such that
\[ v(t, x) \perp T_x \mu' \quad \text{for } \mu\text{-almost all } (t, x) \in \Omega_T, \] (3.1)
\[ \left| \int_0^T \int_{\Omega} (\partial_t \eta + \nabla \eta \cdot v) \, d\mu' \, dt \right| \leq C \|\eta\|_{C^0(\Omega_T)} \] (3.2)
for all $\eta \in C^1_c((0, T) \times \overline{\Omega})$, then we call the evolution $(\mu'_t)_{t \in (0, T)}$ an $L^2$-flow. A function $v \in L^2(\mu, \mathbb{R}^n)$ satisfying (3.1), (3.2) is called a generalized velocity vector.
This definition is based on the observation that for a smooth evolution $(M_t)_{t \in (0, T)}$ with mean curvature $H(t, \cdot)$ and normal velocity vector $V(t, \cdot)$,

$$\frac{d}{dt} \int_{M_t} \eta(t, x) \, dH^{n-1}(x) - \int_{M_t} \partial_t \eta(t, x) \, dH^{n-1}(x) - \int_{M_t} \nabla \eta(t, x) \cdot V(t, x) \, dH^{n-1}(x) = \int_{M_t} H(t, x) \cdot V(t, x) \eta(t, x) \, dH^{n-1}(x).$$

Integrating this equality in time implies (3.2) for any evolution with square-integrable velocity and mean curvature.

**Remark 3.2** Choosing $\eta(t, x) = \zeta(t) \psi(x)$ with $\zeta \in C^1_c((0, T))$, $\psi \in C^1(\Omega)$, we deduce from (3.2) that $t \mapsto \mu^t(\psi)$ belongs to $BV(0, T)$. Choosing a countable dense subset $(\psi_i)_{i \in \mathbb{N}} \subset C^0(\Omega)$, this implies that there exists a countable set $S \subset (0, T)$ of singular times such that any good representative of $t \mapsto \mu^t(\psi)$ is continuous in $(0, T) \setminus S$ for all $\psi \in C^1(\Omega)$.

Any generalized velocity is (on a set of good points) uniquely determined by the evolution $(\mu^t)_{t \in (0, T)}$.

**Proposition 3.3** Let $(\mu^t)_{t \in (0, T)}$ be an $L^2$-flow and set $\mu := L^1 \otimes \mu^t$. Let $v \in L^2(\mu)$ be a generalized velocity field in the sense of Definition 3.1. Then

$$\left( \begin{array}{c} \frac{1}{v(t_0, x_0)} \\ v(t_0, x_0) \end{array} \right) \in T_{(t_0, x_0)}\mu$$

at $\mu$-almost all points $(t_0, x_0) \in \Omega_T$ where the tangential plane of $\mu$ exists. The evolution $(\mu^t)_{t \in (0, T)}$ uniquely determines $v$ at all points $(t_0, x_0) \in \Omega_T$ where both tangential planes $T_{(t_0, x_0)}\mu$ and $T_{(t_0, x_0)}\mu_{b_0}$ exist.

We postpone the proof to Section 8.

On the set of points where a tangential plane of $\mu$ exists, the generalized velocity field $v$ coincides with the normal velocity introduced in 4.

We now turn to the statement of a lower bound for sequences $(u_\varepsilon)_{\varepsilon > 0}$ satisfying Assumption 2.1. As $\varepsilon \to 0$ we will obtain a phase indicator function $u$ as the limit of the sequence $(u_\varepsilon)_{\varepsilon > 0}$ and an $L^2$-flow $(\mu^t)_{t \in (0, T)}$ as the limit of the measures $(\mu_\varepsilon)_{\varepsilon > 0}$. We will show that at $H^n$-almost all points of the phase boundary $\partial^*\{u = 1\} \cap \Omega_T$ the tangential plane of $\mu$ exists. This implies the existence of a unique normal velocity field of the phase boundary.

4. Lower bound for the action functional

We state a lower bound for the functionals $S_\varepsilon$ in several steps. We postpone all proofs to Sections 5–8.

4.1 Lower estimate for the mean curvature

We start with an application of the well-known results of Modica and Mortola [22, 21].
PROPPOSITION 4.1 There exists $u \in BV(\Omega_T; \{-1, 1\}) \cap L^\infty(0, T; BV(\Omega))$ such that for a subsequence $\varepsilon \to 0$,

$$u_\varepsilon \to u \quad \text{in } L^1(\Omega_T),$$

$$u_\varepsilon(t, \cdot) \to u(t, \cdot) \quad \text{in } L^1(\Omega) \text{ for almost all } t \in (0, T).$$

Moreover,

$$\frac{c_0}{2} \int_{\Omega_T} d|\nabla' u| \leq A_3 + T A_4, \quad \frac{c_0}{2} \int_{\Omega} d|\nabla u(t, \cdot)| \leq A_4$$

(4.3)

where $c_0$ was defined in (1.4).

The next proposition basically repeats the arguments in [18, Theorem 1.1].

PROPPOSITION 4.2 There exists a countable set $S \subset (0, T)$, a subsequence $\varepsilon \to 0$ and Radon measures $\mu_t$, $t \in [0, T] \setminus S$, such that for all $t \in [0, T] \setminus S$,

$$\mu_\varepsilon(t) \to \mu_t \text{ as Radon measures on } \overline{\Omega},$$

$$\mu = L^1 \otimes \mu_{\varepsilon^t},$$

(4.5)

and for all $\psi \in C^1(\Omega)$ the function

$$t \mapsto \mu_t(\psi)$$

is of bounded variation in $(0, T)$

(4.6)

and has no jumps in $(0, T) \setminus S$.

Exploiting the lower bound [28] for the diffuse approximation of the Willmore functional [18] we find that the measures $\mu_t$ are integer-rectifiable up to a constant with a weak mean curvature satisfying an appropriate lower estimate.

THEOREM 4.3 For almost all $t \in (0, T)$,

- $(1/c_0)\mu_t$ is an integral $(n - 1)$-varifold,
- $\mu_t$ has weak mean curvature $H(t, \cdot) \in L^2(\mu_t),$ and

$$\int_{\Omega_T} |H|^2 \, d\mu \leq \liminf_{\varepsilon \to 0} \int_{\Omega_T} \frac{1}{\varepsilon} w^2_\varepsilon \, dx \, dt.$$  

(4.7)

4.2 Lower estimate for the generalized velocity

THEOREM 4.4 Let $(\mu_{\varepsilon})_{\varepsilon \in (0, T)}$ be the limit measures obtained in Proposition 4.2. Then there exists a generalized velocity $v \in L^2(\mu, \mathbb{R}^n)$ of $(\mu_{\varepsilon})_{\varepsilon \in (0, T)}$. Moreover,

$$\int_{\Omega_T} |v|^2 \, d\mu \leq \liminf_{\varepsilon \to 0} \int_{\Omega_T} \varepsilon (\partial_{t} u_\varepsilon)^2 \, dx \, dt.$$  

(4.8)

In particular, $(\frac{1}{c_0^{\varepsilon}} \mu_{\varepsilon})_{\varepsilon \in (0, T)}$ is an $L^2$-flow.

We obtain $v$ as a limit of suitably defined approximate velocities (see Lemma 6.2). On the phase boundary $v$ coincides with the (standard) distributional velocity of the bulk phase $\{u(t, \cdot) = 1\}$. However, our definition extends the velocity also to ‘hidden boundaries’, which seems necessary in order to prove the Gamma-convergence of the action functional; see the discussion in Section 9.
**Proposition 4.5** Define the *generalized normal velocity* \( V \) in the direction of the inner normal of \([u = 1]\) by
\[
V(t, x) := \frac{\nabla u}{|\nabla u|}(t, x) \quad \text{for} \quad (t, x) \in \partial^* [u = 1].
\]

Then \( V \in L^1(|\nabla u|) \) and \( V|_{\partial^* [u = 1]} \) is the unique vector field that satisfies, for all \( \eta \in C^1_c(\Omega_T) \),
\[
\int_0^T \int_\Omega V(t, x) \eta(t, x) \, d\|
abla u(t, \cdot)\| \, dx \, dt = - \int_{\Omega_T} u \partial_t \eta \, dx \, dt.
\] (4.9)

**4.3 Lower estimate of the action functional**

As our main result we obtain the following lower estimate for \( S_\varepsilon \).

**Theorem 4.6** Let Assumption 2.1 hold, and let \( \mu, (\mu_t)_{t \in [0, T]}, \) and \( S \) be the measures and the countable set of singular times that we obtained in Proposition 4.2. Define the *nucleation cost* \( S_{\text{nuc}}(\mu) \) by
\[
S_{\text{nuc}}(\mu) := \sum_{t_0 \in S} \sup_{\psi} \left( \lim_{t \searrow t_0} \mu_t(\psi) - \lim_{t \nearrow t_0} \mu_t(\psi) \right) + \sup_{\psi} \left( \lim_{t \searrow 0} \mu_t(\psi) - \mu_0(\psi) \right) + \sup_{\psi} \left( \mu_T(\psi) - \lim_{t \nearrow T} \mu_t(\psi) \right),
\] (4.10)
where the sup is taken over all \( \psi \in C^1(\mathbb{R}) \) with \( 0 \leq \psi \leq 1 \). Then
\[
\liminf_{\varepsilon \to 0} S_\varepsilon(u_\varepsilon) \geq \int_{\Omega_T} v - H^2 \, d\mu + 4 S_{\text{nuc}}(\mu).
\] (4.11)

In the previous definition of nucleation cost we have tacitly chosen good representatives of \( \mu_t(\psi) \) (see [3]). With this choice the jump parts in (4.10) are well-defined.

Finally, let us remark that, in view of Theorem 4.3, \( S_{\text{nuc}} \) does indeed measure only \((n - 1)\)-dimensional jumps.

**Theorem 4.6** improves [17] in the higher-multiplicity case. We will discuss our main results in Section 9.

**4.4 Convergence of the Allen–Cahn equation to mean curvature flow**

Let \( n = 2, 3 \) and consider solutions \( (u_\varepsilon)_{\varepsilon > 0} \) of the Allen–Cahn equation (1.6) satisfying (A2) and (A3). Then \( S_\varepsilon(u_\varepsilon) = 0 \) and the results of Sections 4.1–4.3 apply: There exists a subsequence \( \varepsilon \to 0 \) such that the phase functions \( u_\varepsilon \) converge to a phase indicator function \( u \), the energy measures \( \mu_t^\varepsilon \) converge to an \( L^2 \)-flow \( (\mu_t)_{t \in (0, T)} \), and
\[
H = v
\] (4.12)
\( \mu \)-almost everywhere, where \( H(t, \cdot) \) denotes the weak mean curvature of \( \mu_t \), and \( v \) is the generalized velocity of \( (\mu_t')_{t \in (0, T)} \) in the sense of Definition 3.1. Moreover \( S_{\text{nuc}}(\mu) = 0 \), which shows that for any nonnegative \( \psi \in C^1(\mathbb{R}) \) the function \( t \mapsto \mu_t(\psi) \) cannot jump upwards. From (1.6) and (5.3) below one infers that for any \( \psi \in C^1(\mathbb{R}) \) and all \( \xi \in C^1_c(0, T) \),
\[
- \int_0^T \partial_t \xi \mu_t^\varepsilon(\psi) \, dt = - \int_{\Omega_T} \xi(t) \left( \frac{1}{\varepsilon} \psi(x) u_{\varepsilon}^2(t, x) + \nabla \psi(x) \cdot \nabla u_{\varepsilon} u_{\varepsilon}(t, x) \right) \, dx \, dt.
\] (4.13)
We will show that suitably defined ‘diffuse mean curvatures’ converge as \( \varepsilon \to 0 \) (see (7.1)). Using this result we can pass to the limit in (4.13) to obtain, for any nonnegative functions \( \psi \in C^1(\Omega) \) and \( \zeta \in C^1(0, T) \),

\[
- \int_0^T \partial_t \zeta \mu^\varepsilon(\psi) \, dt \leq - \int_0^T \zeta(t) \int_{\Omega} (H(t,x)^2 + \nabla \psi(x) \cdot H(t,x)) \, d\mu^\varepsilon(x) \, dt,
\]

which is a time-integrated version of Brakke’s inequality.

5. Proofs of Propositions 4.1, 4.2 and Theorem 4.3

Proof of Proposition 4.1. By (2.1), (2.2) we obtain

\[
\int_{\Omega_T} \left( \frac{\varepsilon}{2} |\nabla u^\varepsilon|^2 + \frac{1}{\varepsilon} W(u^\varepsilon) \right) \, dx \, dt \leq A_3 + TA_4.
\]

This implies by (21) the existence of a subsequence \( \varepsilon \to 0 \) and a function \( u \in BV(\Omega_T; \{-1, 1\}) \) such that

\[
u^\varepsilon \to u \quad \text{in} \quad L^1(\Omega_T)
\]

and

\[
c_0 \int_{\Omega_T} d|\nabla u| \leq \liminf_{\varepsilon \to 0} \int_{\Omega_T} \left( \frac{\varepsilon}{2} |\nabla u^\varepsilon|^2 + \frac{1}{\varepsilon} W(u^\varepsilon) \right) \, dx \, dt \leq A_3 + TA_4.
\]

After possibly taking another subsequence, for almost all \( t \in (0, T) \),

\[
u^\varepsilon(t, \cdot) \to u(t, \cdot) \quad \text{in} \quad L^1(\Omega).
\] (5.1)

Using (2.2) and applying (21) for a fixed \( t \in (0, T) \) with (5.1) we get

\[
c_0 \int_{\Omega} d|\nabla u|(t, \cdot) \leq \liminf_{\varepsilon \to 0} \mu^\varepsilon(t, \Omega) \leq A_4.
\]

Before proving Proposition 4.2, we show that the time derivative of the energy densities \( \mu^\varepsilon_t \) is controlled.

Lemma 5.1 There exists \( C = C(A_1, A_3, A_4) \) such that for all \( \psi \in C^1(\Omega_T) \),

\[
\int_0^T |\partial_t \mu^\varepsilon_t(\psi)| \, dt \leq C\|\psi\|_{C^1(\Omega_T)}.
\] (5.2)

Proof. Using (A3) we compute that

\[
2\partial_t \mu^\varepsilon_t(\psi) = \int_{\Omega} \left( \sqrt{\varepsilon} \partial_t u^\varepsilon + \frac{1}{\sqrt{\varepsilon}} w^\varepsilon \right)^2 (t, x) \psi(x) \, dx - \int_{\Omega} \left( \varepsilon (\partial_t u^\varepsilon)^2 + \frac{1}{\varepsilon} w^\varepsilon \right)(t, x) \psi(x) \, dx
\]

\[= - 2 \int_{\Omega} \varepsilon \nabla \psi(x) \cdot \partial_t u^\varepsilon(t, x) \nabla u^\varepsilon(t, x) \, dx.
\] (5.3)
By (2.1), (2.2) we estimate
\[
\left| 2 \int_{\Omega^T} \epsilon \nabla \psi \cdot \partial_t u \nabla u_t \, dx \, dt \right| \leq \int_{\Omega^T} |\nabla \psi| ((\partial_t u)^2 + \epsilon |\nabla u_t|^2) \, dx \, dt \\
\leq (A_3 + T A_4) \|\nabla \psi\|_{C^0(\overline{\Omega^T})},
\]
and deduce from (A1), (2.1), (5.3) that
\[
\int_0^T |\partial_t \mu'_t(\psi)| \, dt \leq (A_1 + A_3) \|\psi\|_{C^0(\overline{\Omega^T})} + C(A_3, T A_4) \|\nabla \psi\|_{C^0(\overline{\Omega^T})},
\]
which proves (5.4).

Proof of Proposition 4.2. By (2.7), \( \mu_\epsilon \to \mu \) as Radon measures on \( \Omega_T \). Choose now a countable family \((\psi_i)_{i \in \mathbb{N}} \subset C^1(\overline{\Omega})\) which is dense in \( C^0(\overline{\Omega}) \). By Lemma 5.1 and a diagonal-sequence argument there exists a subsequence \( \epsilon_n \to 0 \) such that
\[
\mu'_n(\psi_i) \to m_i(t) \quad \text{for almost all } t \in (0, T),
\]
\[
\partial_t \mu'_n(\psi_i) \to m'_j \quad \text{as Radon measures on } (0, T).
\]
Let \( S \) denote the countable set of times \( t \in (0, T) \) where for some \( i \in \mathbb{N} \) the measure \( m_i \) has an atomic part in \( t \). We claim that (5.5) holds on \( (0, T) \setminus S \). To see this we choose a point \( t \in (0, T) \setminus S \) and a sequence of points \((t_j)_{j \in \mathbb{N}} \) in \( (0, T) \setminus S \) such that \( t_j \nrightarrow t \) and (5.5) holds for all \( t_j \). We then obtain
\[
\lim_{j \to \infty} m'_j([t_j, t]) = 0 \quad \text{for all } i \in \mathbb{N},
\]
\[
\lim_{\epsilon \to 0} \partial_t \mu'_\epsilon(\psi_i)([t_j, t]) = m'_j([t_j, t]) \quad \text{for all } i, j \in \mathbb{N}.
\]
Moreover,
\[
|m_i(t) - \mu'_\epsilon(\psi_i)| \leq |m_i(t) - m_i(t_j)| + |m_i(t_j) - \mu'_\epsilon(\psi_i)| + |\mu'_\epsilon(\psi_i) - \mu'_\epsilon(\psi_j)| \\
\leq |m'_j([t_j, t])| + |m_i(t_j) - \mu'_\epsilon(\psi_i)| + |\partial_t \mu'_\epsilon(\psi_i)([t_j, t])|.
\]
Taking first \( \epsilon \to 0 \) and then \( t_j \nrightarrow t \) we deduce from (5.7), (5.8) that (5.5) holds for all \( i \in \mathbb{N} \) and all \( t \in (0, T) \setminus S \).

Take now an arbitrary \( t \in (0, T) \) such that (5.5) holds. By (2.2) there exists a subsequence \( \epsilon \to 0 \) such that
\[
\mu'_\epsilon \to \mu' \quad \text{as Radon measures on } \Omega.
\]
We deduce that \( \mu'(\psi_i) = m_i(t) \) and since \((\psi_i)_{i \in \mathbb{N}} \) is dense in \( C^0(\overline{\Omega}) \) we can identify any limits of \( (\mu'_\epsilon)_{\epsilon \to 0} \) and obtain (5.9) for the whole sequence selected in (5.5), (5.6) and for all \( t \in (0, T) \) for which (5.5) holds. Moreover, for any \( \psi \in C^0(\overline{\Omega}) \) the map \( t \mapsto \mu'_\epsilon(\psi) \) has no jumps in \( (0, T) \setminus S \). After possibly taking another subsequence we can also ensure that as \( \epsilon \to 0 \),
\[
\mu'_\epsilon \to \mu^0, \quad \mu_T' \to \mu^T
\]
as Radon measures on \( \overline{\Omega} \). This proves (4.4).
By the dominated convergence theorem we conclude that for any \( \eta \in C^0(\overline{\Omega_T}) \),

\[
\int_{\Omega_T} \eta \, d\mu = \lim_{\varepsilon \to 0} \int_{\Omega_T} \eta \, d\mu_\varepsilon = \lim_{\varepsilon \to 0} \int_0^T \int_{\Omega} \eta(t, x) \, d\mu_\varepsilon^t(x) \, dt = \int_0^T \int_{\Omega} \eta(t, x) \, d\mu^t(x) \, dt,
\]
which implies (4.5).

By (5.2), the \( L^1(0, T) \)-compactness of sequences that are uniformly bounded in \( BV(0, T) \), the lower semicontinuity of the \( BV \)-norm under \( L^1 \)-convergence, and (4.4) we conclude that (4.6) holds.

**Proof of Theorem 4.3.** Fatou’s lemma and (2.1), (2.2) imply that for almost all \( t \in (0, T) \),

\[
\liminf_{\varepsilon \to 0} \left( \mu^t_\varepsilon(\Omega) + \int_{\Omega} \frac{1}{\varepsilon} w_\varepsilon(t, x)^2 \, dx \right) < \infty. \tag{5.10}
\]

Let \( S \subset (0, T) \) be as in Proposition 4.2 and fix a \( t \in (0, T) \setminus S \) such that (5.10) holds. Then we deduce from [28, Theorems 4.1 and 5.1] and (4.4) that

\[
\frac{1}{c_0} \mu^t \text{ is an integral } (n - 1)\text{-varifold, } \mu^t \geq \frac{c_0}{2} |\nabla u(t, \cdot)|,
\]
and \( \mu^t \) has weak mean curvature \( H(t, \cdot) \) satisfying

\[
\int_{\Omega} |H(t, x)|^2 \, d\mu^t(x) \leq \liminf_{\varepsilon \to 0} \frac{1}{\varepsilon} \int_{\Omega} w_\varepsilon(t, x)^2 \, dx. \tag{5.11}
\]

By (5.11) and Fatou’s lemma we obtain

\[
\int_0^T \int_{\Omega} |H(t, x)|^2 \, d\mu^t(x) \, dt \leq \int_0^T \left( \liminf_{\varepsilon \to 0} \frac{1}{\varepsilon} \int_{\Omega} w_\varepsilon(t, x)^2 \, dx \right) \, dt \leq \liminf_{\varepsilon \to 0} \frac{1}{\varepsilon} \int_{\Omega_T} w_\varepsilon^2 \, dx \, dr,
\]
which proves (4.7).

For later use we also associate general varifolds to \( \mu^t_\varepsilon \) and consider their convergence as \( \varepsilon \to 0 \). Let \( v_\varepsilon(t, \cdot) : \Omega \to S_n^{n-1}(0) \) be an extension of \( \nabla u_\varepsilon(t, \cdot) \) to the set \( \{ \nabla u_\varepsilon(t, \cdot) = 0 \} \). Define the projections \( P_\varepsilon(t, x) := \text{Id} - v_\varepsilon(t, x) \otimes v_\varepsilon(t, x) \) and consider the general varifolds \( V_\varepsilon^t \) and the integer rectifiable varifold \( c_0^{-1} V^t \) defined by

\[
V_\varepsilon^t(f) := \int_{\Omega_T} f(x, P_\varepsilon(t, x)) \, d\mu_\varepsilon^t(x), \tag{5.12}
\]
\[
V^t(f) := \int_{\Omega_T} f(x, P(t, x)) \, d\mu^t(x). \tag{5.13}
\]

for \( f \in C^0_c(\Omega \times \mathbb{R}^{n \times n}) \), where \( P(t, x) \in \mathbb{R}^{n \times n} \) denotes the projection onto the tangential plane \( T_x \mu^t \). Then we deduce from the proof of [28] Theorem 4.1] that

\[
V_\varepsilon^t \to V^t \quad \text{as } \varepsilon \to 0 \tag{5.14}
\]
in the sense of varifolds. \qed
6. Proof of Theorem 4.4

6.1 Equipartition of energy

We start with a preliminary result, showing the important equipartition of energy; the discrepancy measure

\[ \xi_{\epsilon} := \left( \frac{\epsilon}{2} |\nabla u_{\epsilon}|^2 - \frac{1}{\epsilon} W(u_{\epsilon}) \right) L^{n+1} \]  

(6.1)

vanishes in the limit \( \epsilon \to 0 \).

To prove this we combine results from [28] with a refined version of Lebesgue’s dominated convergence theorem [25] (see also [27, Lemma 4.2]).

**Proposition 6.1** For a subsequence \( \epsilon \to 0 \),

\[ |\xi_{\epsilon}| \to 0 \quad \text{as Radon measures on } \Omega. \]  

(6.2)

**Proof.** Let us define the measures

\[ A_{\epsilon} := \left( \frac{\epsilon}{2} |\nabla u_{\epsilon}|^2 - \frac{1}{\epsilon} W(u_{\epsilon}) \right) L^n \]  

on \( \Omega \). For \( \epsilon > 0 \), we define the sets

\[ B_{\epsilon,k} := \left\{ t \in (0, T) : \int_{\Omega} \frac{1}{\epsilon} w_{\epsilon}(t, x)^2 \, dx > k \right\}. \]  

(6.3)

We then deduce from (6.1) that

\[ A_{\epsilon} \geq \int_0^T \int_{\Omega} \frac{1}{\epsilon} w_{\epsilon}(t, x)^2 \, dx \, dt \geq |B_{\epsilon,k}| k. \]  

(6.4)

Next we define the (signed) Radon measures \( \xi_{\epsilon,k} \) by

\[ \xi_{\epsilon,k} := \begin{cases} \xi_{\epsilon} & \text{for } t \in (0, T) \setminus B_{\epsilon,k}, \\ 0 & \text{for } t \in B_{\epsilon,k}. \end{cases} \]  

(6.5)

By [28] Proposition 4.9, we have

\[ |\xi_{\epsilon,j}| \to 0 \quad (j \to \infty) \quad \text{as Radon measures on } \Omega \]  

(6.6)

for any subsequence \( \epsilon_j \to 0 \) (\( j \to \infty \)) such that

\[ \limsup_{j \to \infty} \int_{\Omega} \frac{1}{\epsilon_j} w_{\epsilon_j}(t, x)^2 \, dx < \infty. \]

By (2.2), (6.5) we deduce that for any \( \eta \in C^0(\overline{\Omega}_T, \mathbb{R}^n_+) \), and almost all \( t \in (0, T) \),

\[ |\xi_{\epsilon,k}^j|((\eta(t, \cdot))) \to 0 \quad \text{as } \epsilon \to 0 \]  

(6.7)

and

\[ |\xi_{\epsilon,k}^j|((\eta(t, \cdot))) = (1 - \lambda_{B_{\epsilon,k}}(t))|\xi_{\epsilon}^j|((\eta(t, \cdot))) \leq A_4 \|\eta\|_{C^0(\overline{\Omega}_T)}. \]  

(6.8)
By the dominated convergence theorem, (6.7) and (6.8) imply that
\[ \int_0^T |\xi_{t,\varepsilon,k}|(\eta(t, \cdot)) \, dt \to 0 \quad \text{as} \quad \varepsilon \to 0. \]  
(6.9)

Further, we obtain
\[ \int_0^T |\xi_{t,\varepsilon}|(\eta(t, \cdot)) \, dt \leq \int_0^T |\xi_{t,\varepsilon,k}|(\eta(t, \cdot)) \, dt + \int_{B_{\varepsilon,k}} |\xi_{t,\varepsilon}|(\eta(t, \cdot)) \, dt + \int_{B_{\varepsilon,k}} \mu_t(\eta(t, \cdot)) \, dt. \]  
(6.10)

For \( k \in \mathbb{N} \) fixed we deduce from (2.2), (6.4), (6.10) that
\[ \limsup_{\varepsilon \to 0} \int_0^T \int_{\Omega} |\xi_{t,\varepsilon}|^2 \, d\tilde{\mu}_\varepsilon(\eta(t, \cdot)) \, dt \leq \lim_{\varepsilon \to 0} \int_0^T |\xi_{t,\varepsilon,k}|(\eta(t, \cdot)) \, dt + \|\eta\|_{C^0(\Omega_T)}^A A_3/k. \]  
(6.11)

By (6.9) and since \( k \in \mathbb{N} \) was arbitrary this proves the proposition.

6.2 Convergence of approximate velocities

In the next step in the proof of Theorem 4.4 we define approximate velocity vectors and show their convergence as \( \varepsilon \to 0 \).

**Lemma 6.2** Define \( v_\varepsilon : \Omega_T \to \mathbb{R}^n \) by
\[ v_\varepsilon := \begin{cases} -\frac{\partial_t u_\varepsilon}{|\nabla u_\varepsilon|} \nabla u_\varepsilon & \text{if} \ |\nabla u_\varepsilon| \neq 0, \\ 0 & \text{otherwise}. \end{cases} \]  
(6.12)

Then there exists a function \( v \in L^2(\mu, \mathbb{R}^n) \) such that
\[ (\varepsilon |\nabla u_\varepsilon|^2 \mathcal{L}^{n+1}, v_\varepsilon) \to (\mu, v) \quad \text{as} \quad \varepsilon \to 0 \]  
(6.13)
in the sense of measure-function pair convergence (see Appendix B) and such that (4.8) is satisfied.

**Proof.** We define Radon measures
\[ \tilde{\mu}_\varepsilon := \varepsilon |\nabla u_\varepsilon|^2 \mathcal{L}^{n+1} + \xi_\varepsilon. \]  
(6.14)

From (2.7), (6.2) we deduce that
\[ \tilde{\mu}_\varepsilon \to \mu \quad \text{as Radon measures on} \ \Omega_T. \]  
(6.15)

Next we observe that \((\tilde{\mu}_\varepsilon, v_\varepsilon)\) is a measure-function pair in the sense of [13] (see also Definition B.1 in Appendix B) and that by (2.1),
\[ \int_{\Omega_T} |v_\varepsilon|^2 \, d\tilde{\mu}_\varepsilon \leq \int_{\Omega_T} \varepsilon (\partial_t u_\varepsilon)^2 \, dx \, dt \leq A_3. \]  
(6.16)

By Theorem B.3, we therefore deduce that there exists a subsequence \( \varepsilon \to 0 \) and a function \( v \in L^2(\mu, \mathbb{R}^n) \) such that (6.13) and (4.8) hold. \( \square \)
Lemma 6.3 For $\mu$-almost all $(t, x) \in \Omega_T$,
\begin{equation}
  v(t, x) \perp T_x \mu^t.
\end{equation}

Proof. We follow [23, Proposition 3.2]. Let $v_\epsilon : \Omega_T \to S^{n-1}_0(0)$ be an extension of $\nabla u_\epsilon / |\nabla u_\epsilon|$ to the set $\{\nabla u_\epsilon = 0\}$ and define projection-valued maps $P_\epsilon : \Omega_T \to \mathbb{R}^{n \times n}$ by
\[ P_\epsilon := \text{Id} - v_\epsilon \otimes v_\epsilon. \]

Consider next the general varifolds $\tilde{V}_\epsilon, V$ defined by
\begin{equation}
  \tilde{V}_\epsilon(f) := \int_{\Omega_T} f(t, x, P_\epsilon(t, x)) \, d\tilde{\mu}_\epsilon(t, x),
\end{equation}
\begin{equation}
  V(f) := \int_{\Omega_T} f(t, x, P(t, x)) \, d\mu(t, x)
\end{equation}
for $f \in C^0_c(\Omega_T \times \mathbb{R}^{n \times n})$, where $P(t, x) \in \mathbb{R}^{n \times n}$ denotes the projection onto the tangential plane $T_x \mu^t$.

From (5.14), Proposition 6.1, and Lebesgue’s dominated convergence theorem we deduce that
\[ \lim_{\epsilon \to 0} \tilde{V}_\epsilon = V \]
as Radon measures on $\Omega_T \times \mathbb{R}^{n \times n}$.

Next we define functions $\hat{v}_\epsilon$ on $\Omega_T \times \mathbb{R}^{n \times n}$ by
\[ \hat{v}_\epsilon(t, x, Y) = v_\epsilon(t, x) \text{ for all } (t, x) \in \Omega_T, Y \in \mathbb{R}^{n \times n}. \]

We then observe that
\[ \int_{\Omega_T \times \mathbb{R}^{n \times n}} \hat{v}_\epsilon^2 \, dV_\epsilon = \int_{\Omega_T} v_\epsilon^2 \, d\tilde{\mu}_\epsilon \leq A_3 \]
and deduce from (6.20) and Theorem B.3 the existence of $\hat{v} \in L^2(V, \mathbb{R}^n)$ such that $(V, \hat{v}_\epsilon)$ converges to $(V, \hat{v})$ as measure-function pairs on $\Omega_T \times \mathbb{R}^{n \times n}$ with values in $\mathbb{R}^n$.

We now consider $h \in C^0_c(\mathbb{R}^{n \times n})$ such that $h(Y) = 1$ for all projections $Y$. We deduce that for any $\eta \in C^0(\Omega_T, \mathbb{R}^n)$,
\begin{align*}
  \int_{\Omega_T} \eta \cdot v \, d\mu &= \lim_{\epsilon \to 0} \int_{\Omega_T \times \mathbb{R}^{n \times n}} \eta(t, x) \cdot h(Y) \hat{v}_\epsilon(t, x, Y) \, dV_\epsilon(t, x, Y) \\
  &= \int_{\Omega_T} \eta(t, x) \cdot \hat{v}(t, x, P(t, x)) \, d\mu(t, x),
\end{align*}
which shows that for $\mu$-almost all $(t, x) \in \Omega_T$,
\[ \hat{v}(t, x, P(t, x)) = v(t, x). \]

Finally, we observe that for $h, \eta$ as above,
\begin{align*}
  \int_{\Omega_T} \eta(t, x) \cdot P(t, x) v(t, x) \, d\mu(t, x) &= \int_{\Omega_T \times \mathbb{R}^{n \times n}} \eta(t, x) h(Y) \cdot Y \hat{v}(t, x, Y) \, dV(t, x, Y) \\
  &= \lim_{\epsilon \to 0} \int_{\Omega_T \times \mathbb{R}^{n \times n}} \eta(t, x) h(Y) \cdot Y \hat{v}_\epsilon(t, x, Y) \, dV_\epsilon(t, x, Y) \\
  &= \lim_{\epsilon \to 0} \int_{\Omega_T} \eta(t, x) \cdot P_\epsilon(t, x) v_\epsilon(t, x) \, d\tilde{\mu}_\epsilon(t, x) = 0
\end{align*}
since $P_\epsilon v_\epsilon = 0$. This shows that $P(t, x) v(t, x) = 0$ for $\mu$-almost all $(t, x) \in \Omega_T$. □
Proof of Theorem 4.4. By (2.1) there exists a subsequence \( \varepsilon \to 0 \) and a Radon measure \( \beta \) on \( \overline{\Omega_T} \) such that
\[
\left( \varepsilon (\partial_t u_\varepsilon)^2 + \frac{1}{\varepsilon} w_\varepsilon^2 \right) L^{n+1} \to \beta, \quad \beta(\overline{\Omega_T}) \leq A_3. \tag{6.22}
\]
Using (A3) we compute that for any \( \eta \in C^1_c((0, T) \times \overline{\Omega}) \),
\[
\int_{\Omega_T} \eta \, d\alpha = \int_{\Omega_T} \eta \left( \varepsilon (\partial_t u_\varepsilon)^2 + \frac{1}{\varepsilon} w_\varepsilon^2 \right) \, dx \, dt - 2 \int_{\Omega_T} \partial_t \eta \, d\mu_\varepsilon + 2 \int_{\Omega_T} \varepsilon \nabla \eta \cdot \partial_t u_\varepsilon \nabla u_\varepsilon \, dx \, dt. \tag{6.23}
\]
As \( \varepsilon \) tends to zero the term on the left-hand side and the first two terms on the right-hand side converge by (2.7), (2.8) and (6.22). For the third term on the right-hand side of (6.23) we find from (6.13) that
\[
\lim_{\varepsilon \to 0} \int_{\Omega_T} \nabla \eta \cdot \partial_t u_\varepsilon \nabla u_\varepsilon \, dx \, dt = - \lim_{\varepsilon \to 0} \int_{\Omega_T} \nabla \eta \cdot v_\varepsilon |\nabla u_\varepsilon|^2 \, dx \, dt = - \int_{\Omega_T} \nabla \eta \cdot v \, d\mu.
\]
Therefore, taking \( \varepsilon \to 0 \) in (6.23) we deduce that
\[
\int_{\Omega_T} \eta \, d\alpha = \int_{\Omega_T} \eta \, d\beta - 2 \int_{\Omega_T} \partial_t \eta \, d\mu + 2 \int_{\Omega_T} \nabla \eta \cdot v \, d\mu
\]
for all \( \eta \in C^1_c((0, T) \times \overline{\Omega}) \). This yields
\[
\left| \int_{\Omega_T} (\partial_t \eta + \nabla \eta \cdot v) \, d\mu \right| \leq \|\eta\|_{C^0(\overline{\Omega_T})} \frac{1}{2} (\alpha(\overline{\Omega_T}) + \beta(\overline{\Omega_T})),
\]
which together with (6.17) shows that \( v \) is a generalized velocity vector for \( (\mu^t)_{t \in (0, T)} \) in the sense of Definition 3.1. The estimate (4.8) was already proved in Lemma 6.2.

7. Proof of Theorem 4.6
We start with the convergence of a `diffuse mean curvature term’.

Lemma 7.1 Define
\[
H_\varepsilon := \frac{1}{\varepsilon} w_\varepsilon \frac{\nabla u_\varepsilon}{|\nabla u_\varepsilon|^2},
\]
let \( \tilde{\mu}_\varepsilon = \varepsilon |\nabla u_\varepsilon|^2 L^{n+1} \), and let \( v_\varepsilon, v \) be as in (6.12), (6.13). Then
\[
(\tilde{\mu}_\varepsilon, H_\varepsilon) \to (\mu, H), \quad (\mu_\varepsilon, v_\varepsilon - H_\varepsilon) \to (\mu, v - H) \tag{7.1}
\]
as \( \varepsilon \to 0 \) in the sense of measure-function pair convergence. In particular
\[
\int_{\Omega_T} |v - H|^2 \, d\mu \leq \alpha(\eta) \tag{7.3}
\]
for all \( \eta \in C^0(\overline{\Omega_T}, \mathbb{R}^+ \).
Proof. We use arguments similar to the proof of Proposition 6.1. For \( \varepsilon > 0, k \in \mathbb{N} \), we define

\[
B_{\varepsilon,k} := \left\{ t \in (0, T) : \int_{\Omega} \frac{1}{\varepsilon} w_{\varepsilon}(t,x)^2 \, dx > k \right\}. \tag{7.4}
\]

We then deduce from (2.1) that

\[
A_3 \geq \int_{\Omega_T} \frac{1}{\varepsilon} w_{\varepsilon}^2 \, dx \, dt \geq |B_{\varepsilon,k}| \varepsilon. \tag{7.5}
\]

Next we define functionals \( T_{\varepsilon,k}^t \in C^0_c(\Omega, \mathbb{R}^n)^* \) by

\[
T_{\varepsilon,k}^t(\psi) := \begin{cases} 
\int_{\Omega} \psi(x) \cdot w_{\varepsilon}(t,x) \nabla u_{\varepsilon}(t,x) \, dx & \text{for } t \in (0, T) \setminus B_{\varepsilon,k}, \\
\int_{\Omega} \psi(x) \cdot H(t,x) \, d\mu^t(x) & \text{for } t \in B_{\varepsilon,k}. 
\end{cases} \tag{7.6}
\]

Considering the general \((n - 1)\)-varifolds \( V_{\varepsilon}^t, V_t \) defined in (5.12), (5.13) we infer from [28, Proposition 4.10] and (5.14) that

\[
\lim_{j \to \infty} \int_{\Omega} \psi \cdot w_{\varepsilon_j}(t,x) \nabla u_{\varepsilon_j}(t,x) \, dx = - \lim_{j \to \infty} \delta V_{\varepsilon_j}^t(\psi) = - \delta \mu^t(\psi) = \int_{\Omega} \psi \cdot H(t,x) \, d\mu^t(x) \tag{7.7}
\]

for any subsequence \( \varepsilon_j \to 0 \) \((j \to \infty)\) such that

\[
\limsup_{j \to \infty} \int_{\Omega} \frac{1}{\varepsilon_j} w_{\varepsilon_j}^2 \, dx \, dt < \infty.
\]

Therefore we deduce from (7.6), (7.7) that for all \( \eta \in C^0_c(\Omega_T, \mathbb{R}^n) \), \( k \in \mathbb{N} \), and almost all \( t \in (0, T) \),

\[
T_{\varepsilon,k}^t(\eta(t, \cdot)) \to \int_{\Omega} \eta(t,x) \cdot H(t,x) \, d\mu^t(x) \quad \text{as } \varepsilon \to 0 \tag{7.8}
\]

and

\[
|T_{\varepsilon,k}^t(\eta(t, \cdot))| \leq (1 - \chi_{B_{\varepsilon,k}}(t)) \int_{\Omega} \eta(t,x) \cdot w_{\varepsilon}(t,x) \nabla u_{\varepsilon}(t,x) \, dx \\
+ \chi_{B_{\varepsilon,k}}(t) \int_{\Omega} \eta(t,x) \cdot H(t,x) \, d\mu^t(x) \\
\leq \|\eta\|_{C^0(\Omega_T)} (1 - \chi_{B_{\varepsilon,k}}(t)) \left( \int_{\Omega} \frac{1}{2\varepsilon} w_{\varepsilon}(t,x)^2 \, dx \right)^{1/2} \left( \int_{\Omega} \frac{\varepsilon}{2} |\nabla u_{\varepsilon}(t,x)|^2 \, dx \right)^{1/2} \\
+ \int_{\Omega} |\eta(t,x)||H(t,x)| \, d\mu^t(x) \\
\leq \|\eta\|_{C^0(\Omega_T)} \sqrt{\frac{1}{2} \sqrt{A_4} + \int_{\Omega} |\eta(t,x)||H(t,x)| \, d\mu^t(x)}, \tag{7.9}
\]

where the right-hand side is bounded in \( L^1(0, T) \), uniformly with respect to \( \varepsilon > 0 \).
By the dominated convergence theorem, (7.8) and (7.9) imply that
\[ \int_0^T T_{\varepsilon,k}(\eta(t,\cdot)) \, dt \to \int_{\Omega_T} \eta \cdot H \, d\mu \quad \text{as } \varepsilon \to 0. \] (7.10)

Further, we obtain
\[ \left| \int_{\Omega_T} \eta \cdot w_{\varepsilon} \nabla u_{\varepsilon} \, dx \, dt - \int_{\Omega_T} \eta \cdot H \, d\mu \right| \leq \left| \int_0^T T_{\varepsilon,k}(\eta(t,\cdot)) \, dt - \int_{\Omega_T} \eta \cdot H \, d\mu \right| \]
\[ + \left| \int_{B_{\varepsilon,k}} \int_{\Omega_T} \eta(t,x) \cdot H(t,x) \, d\mu'(x) \, dt \right| + \left| \int_{B_{\varepsilon,k}} \int_{\Omega_T} \eta \cdot w_{\varepsilon} \nabla u_{\varepsilon} \, dx \, dt \right|. \] (7.11)

The last term on the right-hand side is estimated by
\[ \left| \int_{B_{\varepsilon,k}} \int_{\Omega_T} \eta(t,x) \cdot w_{\varepsilon}(t,x) \nabla u_{\varepsilon}(t,x) \, dx \, dt \right| \leq \| \eta \|_{C^0(\Omega_T)} \left( \int_{\Omega_T} \frac{1}{2} w_{\varepsilon}^2 \, dx \, dt \right)^{1/2} |B_{\varepsilon,k}| \frac{1}{\sqrt{k}} \sqrt{A_4}. \] (7.12)

where we have used (2.2) and (7.5). For the second term on the right-hand side of (7.11) we obtain
\[ \left| \int_{B_{\varepsilon,k}} \int_{\Omega_T} \eta(t,x) \cdot H(t,x) \, d\mu'(x) \, dt \right| \leq \sqrt{A_3} \frac{\| \eta \|_{C^0(\Omega_T)}}{\sqrt{k}} \sqrt{A_3}. \] (7.13)

where we have used (4.7) and (2.1). Finally, for \( k \in \mathbb{N} \) fixed, by (7.10) we deduce that
\[ \lim_{\varepsilon \to 0} \left| \int_0^T T_{\varepsilon,k}(\eta(t,\cdot)) \, dt - \int_{\Omega_T} \eta \cdot H \, d\mu \right| = 0. \] (7.14)

Taking \( \varepsilon \to 0 \) in (7.11) we find by (7.12)–(7.14) that
\[ \lim_{\varepsilon \to 0} \left| \int_{\Omega_T} \eta \cdot w_{\varepsilon} \nabla u_{\varepsilon} \, dx \, dt - \int_{\Omega_T} \eta \cdot H \, d\mu \right| \leq \frac{A_3}{\sqrt{k}} \| \eta \|_{C^0(\Omega_T)} \sqrt{A_4} + \frac{1}{\sqrt{k}} A_3 \] (7.15)

for any \( k \in \mathbb{N} \), which proves (7.11). Together with (6.13) this implies (7.2). Finally, we fix an arbitrary nonnegative \( \eta \in C^0(\Omega_T) \) and deduce that the measure-function pair \((\mu_{\varepsilon}, \sqrt{\eta}(v_{\varepsilon} - H_{\varepsilon}))\) converges to \((\mu, \sqrt{\eta}(v - H))\). The estimate (7.3) then follows from Theorem B.3.

Let \( \Pi : [0, T] \times \mathbb{R}^d \to [0, T] \) denote the projection onto the first component and \( \Pi_\theta \) the pushforward of measures by \( \Pi \). For \( \psi \in C^0(\mathbb{R}^d) \) we consider the measures
\[ \alpha_\psi := \Pi_\theta(\alpha_\psi), \]
on $[0, T]$, that is,
\[
\alpha_\psi(\zeta) := \int_{\Omega_T} \zeta(t) \psi(x) \, d\alpha(t, x) \quad \text{for } \zeta \in C^0([0, T]),
\]
and set
\[
\alpha_\Omega := \Pi_{\alpha} \alpha.
\]
We can then estimate the atomic part of $\alpha_\Omega$ in terms of the nucleation cost.

**Lemma 7.2** Let $S_{\text{nuc}}(\mu)$ be the nucleation cost defined in (4.10). Then
\[
(\alpha_\Omega)_{\text{atomic}}[0, T] \geq 4 S_{\text{nuc}}(\mu). \tag{7.16}
\]

**Proof.** Let $\eta \in C^1(\overline{\Omega_T}, \mathbb{R}^+_0)$ be nonnegative. We compute that
\[
\int_{\Omega_T} \eta \, d\alpha = \int_{\Omega_T} \eta \left( \varepsilon (\partial_t u_\varepsilon)^2 + \frac{1}{\varepsilon} w_\varepsilon^2 + 2 \partial_t u_\varepsilon w_\varepsilon \right) \, dx \, dt \geq 4 \int_{\Omega_T} \eta \partial_t u_\varepsilon \, dx \, dt
\]
\[
= -4 \int_{\Omega_T} \partial_t \eta \, d\mu + 4 \int_{\Omega_T} \nabla \eta \cdot \varepsilon \partial_t u_\varepsilon \nabla u_\varepsilon \, dx \, dt + 4 \mu_T(\eta(T, \cdot)) - 4 \mu_0^0(\eta(0, \cdot)). \tag{7.17}
\]
Passing to the limit $\varepsilon \to 0$ we infer from (2.7), (4.4), (6.13) that
\[
\int_{\Omega_T} \eta \, d\alpha \geq -4 \int_{\Omega_T} \partial_t \eta \, d\mu + 4 \int_{\Omega_T} \nabla \eta \cdot v \, d\mu + 4 \mu^T(\eta(T, \cdot)) - 4 \mu_0^0(\eta(0, \cdot)). \tag{7.18}
\]
We now choose $\eta(t, x) = \zeta(t) \psi(x)$ where $\zeta \in C^1([0, T], \mathbb{R}^+_0)$, $\psi \in C^1(\overline{\Omega}, \mathbb{R}^+_0)$ in (7.18) and deduce that
\[
\int_0^T \zeta \, d\alpha_\psi \geq -4 \int_0^T \partial_t \zeta \mu^T(\psi) \, dt + 4 \int_0^T \zeta \int_{\Omega} \nabla \psi \cdot v(t, x) \, d\mu^T(x) \, dt + 4 \zeta(T) \mu^T(\psi) - 4 \zeta(0) \mu_0^0(\psi). \tag{7.19}
\]
This shows that
\[
\alpha_\psi \geq 4 \partial_t (\mu^T(\psi)) + 4 \left( \int_{\Omega} \nabla \psi(x) \cdot v(t, x) \, d\mu^T(x) \right) L^1
\]
\[
+ 4(\mu^T(\psi) - \lim_{t \uparrow T} \mu^T(\psi)) \delta_T + 4(\lim_{t \downarrow 0} \mu^T(\psi) - \mu_0^0(\psi)) \delta_0. \tag{7.20}
\]
Evaluating the atomic parts we see that for any $0 < t_0 < T$,
\[
\alpha_\psi([t_0]) \geq 4 \partial_t (\mu^T(\psi))(t_0),
\]
which implies that
\[
\alpha_\Omega([t_0]) \geq 4 \sup_{\psi} \partial_t (\mu^T(\psi))(t_0), \tag{7.21}
\]
where the supremum is taken over all $\psi \in C^1(\overline{\Omega})$ with $0 \leq \psi \leq 1$. 

Moreover we deduce from (7.20) that
\[ \alpha_{\Omega}(\{0\}) \geq 4 \sup_{\psi} \mu_{\Omega}^1(\psi) - \mu_0^0(\psi), \] (7.22)
and from (7.21) that
\[ \alpha_{\Omega}(\{T\}) \geq 4 \sup_{\psi} \mu_{\Omega}^T(\psi) - \lim_{t \uparrow T} \mu_{\Omega}^t(\psi), \] (7.23)
where the supremum is taken over \( \psi \in C(\Omega) \) with \( 0 \leq \psi \leq 1 \). By (7.21)–(7.23) we conclude that (7.16) holds.

**Proof of Theorem 4.6.** By (7.3) we know that \( \alpha \geq |v - H|^2 \mu \). Since \( \mu = L^1 \otimes \mu^1 \) we deduce from the Radon–Nikodym theorem that
\[ (\alpha_{\Omega})_{ac}[0, T] \geq \int_{\Omega \times [0, T]} |v - H|^2 d\mu, \] (7.24)
and from (7.16) that
\[ (\alpha_{\Omega})_{atomic}[0, T] \geq 4 S_{\text{nuc}}(\mu), \] (7.25)
where \((\alpha_{\Omega})_{ac}\) and \((\alpha_{\Omega})_{atomic}\) denote the absolutely continuous and atomic parts of the measure \( \alpha_{\Omega} \) with respect to \( L^1 \). Adding the two estimates and recalling (2.9) we obtain (4.11).

**8. Proofs of Propositions 3.3 and 4.5**

For \( r > 0 \), \((t_0, x_0) \in \Omega_T\) define the cylinders
\[ Q_r(t_0, x_0) := \{(t, x, y) \in \Omega_T : t \in [t_0 - r, t_0 + r] \times B^n_r(x_0)\}. \]

**Proof of Proposition 3.3**

Define
\[ \Sigma_n(\mu) := \{ (t, x) \in \Omega_T : \text{the tangential plane of } \mu \text{ at } (t, x) \text{ exists} \} \] (8.1)
and choose \((t_0, x_0) \in \Sigma_n(\mu)\) such that
\[ v \text{ is approximately continuous with respect to } \mu \text{ at } (t_0, x_0). \] (8.2)

Since \( v \in L^2(\mu) \) we deduce from [10] Theorem 2.9.13 that (8.2) holds \( \mu \)-almost everywhere. Let
\[ P_0 := T_{(t_0, x_0)}\mu, \quad \theta_0 > 0, \] (8.3)
denote the tangential plane and multiplicity at \((t_0, x_0)\) respectively, and define for any \( \varphi \in C^0_0(Q_1(0)) \) the scaled functions \( \varphi_\theta \in C^0_0(Q_\theta(t_0, x_0)) \) by
\[ \varphi_\theta(t, x) := \varphi(\theta^{-1}(t - t_0), \theta^{-1}(x - x_0)). \]

Then (8.3) shows that
\[ \int_{\Omega_T} \varphi_\theta d\mu \to \theta_0 \int_{P_0} \varphi d\mathcal{H}^n \text{ as } \theta \searrow 0. \] (8.4)
From (3.2), the Hahn–Banach theorem, and the Riesz theorem we deduce that the functional
\[ \vartheta \in C^1_c(\Omega_T)^*, \quad \vartheta(\eta) := \int_{\Omega_T} \nabla' \eta \cdot \left( \frac{1}{v} \right) \, d\mu, \] (8.5)
can be extended to a (signed) Radon measure on \( \Omega_T \). Since by the Radon–Nikodym theorem, \( D_\mu |\vartheta| \) exists and is finite \( \mu \)-almost everywhere, we may assume without loss of generality that
\[ D_\mu |\vartheta|(t_0, x_0) < \infty. \] (8.6)

We next fix \( \eta \in C^1_c(Q_1(0)) \) and compute
\[ \vartheta(\rho \eta) = \int_{\Omega_T} \nabla' \eta \cdot \left( \frac{1}{v} \right) \, d\mu. \] (8.7)

From (8.2), (8.4) we deduce that the right-hand side converges as \( \rho \to 0 \),
\[ \lim_{\rho \to 0} \int_{\Omega_T} \nabla' \eta \cdot \left( \frac{1}{v} \right) \, d\mu = \theta_0 \left( \frac{1}{v(t_0, x_0)} \right) \cdot \int_{P_0} \nabla' \eta \, d\mu. \] (8.8)

For the left-hand side of (8.7) we deduce that
\[ \liminf_{\rho \downarrow 0} |\vartheta(\rho \eta)| \leq \|\eta\|_{C^0_c(Q_1(0))} \liminf_{\rho \downarrow 0} \rho^{-n+1} |\vartheta|(Q_\rho(t_0, x_0)) \] (8.9)
and observe that (8.6) implies
\[ \infty > \lim_{\rho \downarrow 0} \frac{|\vartheta|(Q_\rho(t_0, x_0))}{\mu(Q_\rho(t_0, x_0))} \geq \liminf_{\rho \downarrow 0} \rho^{-n} |\vartheta|(Q_\rho(t_0, x_0)) \cdot \left( \limsup_{\rho \downarrow 0} \rho^{-n} \mu(Q_\rho(t_0, x_0)) \right)^{-1} \]
\[ \geq c \liminf_{\rho \downarrow 0} \rho^{-n} |\vartheta|(Q_\rho(t_0, x_0)), \] (8.10)
since by (8.4) for any \( \varphi \in C^0_c(Q_2(0), \mathbb{R}_0^+) \) with \( \varphi \geq 1 \) on \( Q_1(0) \),
\[ \limsup_{\rho \downarrow 0} \rho^{-n} \mu(Q_\rho(t_0, x_0)) \leq \limsup_{\rho \downarrow 0} \int_{Q_\rho(0, x_0)} \varphi \, d\mu \leq C(\varphi). \]

Therefore (8.7)–(8.10) yield
\[ \theta_0 \left( \frac{1}{v(t_0, x_0)} \right) \cdot \int_{P_0} \nabla' \eta \, d\mu = 0. \] (8.11)

Now we observe that the integral over the projection of \( \nabla' \eta \) onto \( P_0 \) vanishes. This shows that
\[ \int_{P_0} \nabla' \eta \, dH^n \in P_0^\perp. \] (8.12)
Since \( \eta \) can be chosen such that the integral in (8.12) takes an arbitrary direction normal to \( P_0 \) we see from (8.11) that \( v(t_0, x_0) \) satisfies (3.3). If \( T_{\eta_0} \mu^0 \) exists then
\[ T_{(t_0, x_0)} \mu = \{0\} \times T_{\eta_0} \mu^0 \oplus \text{span} \left( \frac{1}{v(x_0)} \right) \]
and we conclude that \( v \) is uniquely determined.
To prepare the proof of Proposition 8.1, we first show that $\mu$ is absolutely continuous with respect to $\mathcal{H}^n$.

**Proposition 8.1** For any $D \subset \Omega$ there exists $C(D) > 0$ such that for all $x_0 \in D$ and almost all $t_0 \in (0, T)$,

\[
\limsup_{r \searrow 0} r^{-n} \mu(Q_r(t_0, x_0)) \leq C(D) A_4 + \liminf_{\varepsilon \to 0} \int_D \frac{1}{\varepsilon} w_\varepsilon(t_0, x)^2 \, dx.
\]

(8.13)

In particular,

\[
\limsup_{\rho \to 0} \frac{\mu(B_\rho(t_0, x_0))}{\rho^n} < \infty \quad \text{for } \mu\text{-almost every } (t_0, x_0)
\]

(8.14)

and $\mu$ is absolutely continuous with respect to $\mathcal{H}^n$,

\[
\mu \ll \mathcal{H}^n.
\]

(8.15)

**Proof.** Let

\[
r_0 := \min \left\{ 1, \frac{1}{2} \text{dist}(D, \partial \Omega), |t_0|, |T - t_0| \right\}.
\]

Then for all $r < r_0$, $x_0 \in D$, from (6.2) and [28, Proposition 4.5] we obtain

\[
\frac{1}{r} \int_{b_0-r}^{t_0+r} r^{1-n} \mu'(B^n_r(x_0)) \, dt \\
\leq \frac{1}{r} \int_{b_0-r}^{t_0+r} r^{1-n} \mu'(B^n_r(x_0)) \, dt + \frac{1}{4(n-1)^2} \frac{1}{r} \int_{b_0-r}^{t_0+r} \left( \liminf_{\varepsilon \to 0} \int_D \frac{1}{\varepsilon} w_\varepsilon(t, x)^2 \, dx \right) \, dt.
\]

(8.16)

By Fatou’s lemma and (2.1),

\[
t \mapsto \liminf_{\varepsilon \to 0} \int_D \frac{1}{\varepsilon} w_\varepsilon(t, x)^2 \, dx \quad \text{is in } L^1(0, T),
\]

(8.17)

and by (2.2) we deduce that for almost all $t_0 \in (0, T)$,

\[
\limsup_{r \searrow 0} \frac{1}{r} \int_{b_0-r}^{t_0+r} r^{1-n} \mu'(B^n_r(x_0)) \, dt \leq 2r_0^{1-n} A_4 + \frac{1}{2(n-1)^2} \liminf_{\varepsilon \to 0} \int_D \frac{1}{\varepsilon} w_\varepsilon(t_0, x)^2 \, dx.
\]

Since $r_0$ depends only on $D$ and $\Omega$, the inequality (8.13) follows.

By (8.17) the right-hand side in (8.13) is finite for $L^1$-almost all $t_0 \in (0, T)$, and $\theta^m(\mu, (t, x))$ is bounded for almost all $t \in (0, T)$ and all $x \in \Omega$. By (2.2) we deduce that for any $I \subset (0, T)$ with $|I| = 0$,

\[
\mu(I \times \Omega) \leq A_4 |I| = 0,
\]

which implies (8.14).

To prove the final statement let $B \subset \Omega_T$ be given with

\[
\mathcal{H}^n(B) = 0.
\]

(8.18)
Consider the family of sets \((D_k)_{k \in \mathbb{N}}\), given by

\[ D_k := \{ z \in \Omega_T : \vartheta^\mu (\mu, z) \leq k \}. \]

By (8.14), [31, Theorem 3.2], and (8.18) we find that for all \(k \in \mathbb{N}\),

\[ \mu (B \cap D_k) \leq 2^n k \mathcal{H}^n (B \cap D_k) = 0. \tag{8.19} \]

Moreover,

\[ \mu \left( B \setminus \bigcup_{k \in \mathbb{N}} D_k \right) = 0 \tag{8.20} \]

by (8.14). By (8.19), (8.20) we conclude that \(\mu (B) = 0\), which proves (8.15).

To prove Proposition 4.5 we need that \(\mathcal{H}^n\)-almost everywhere on \(\partial^* \{ u = 1 \}\) the generalized tangent plane of \(\mu\) exists. We first obtain the following relation between the measures \(\mu\) and \(|\nabla' u|\).

**Proposition 8.2** There exists a nonnegative function \(g \in L^2(\mu, \mathbb{R}_0^+)\) such that

\[ g \mu \geq \frac{c_0}{2} |\nabla' u|. \tag{8.21} \]

In particular, \(|\nabla' u|\) is absolutely continuous with respect to \(\mu\),

\[ |\nabla' u| \ll \mu. \tag{8.22} \]

**Proof.** Let

\[ G(r) = \int_0^r \sqrt{2W(s)} \, ds. \tag{8.23} \]

On the set \(|\nabla u_\varepsilon| \neq 0\) we have

\[ |\nabla G(u_\varepsilon)| = \frac{|\nabla G(u_\varepsilon)|}{|\nabla' G(u_\varepsilon)|} \cdot |\nabla' G(u_\varepsilon)| = \frac{|\nabla G(u_\varepsilon)|}{\sqrt{\partial_\varepsilon G(u_\varepsilon)^2 + |\nabla' G(u_\varepsilon)|^2}} \frac{|\nabla' G(u_\varepsilon)|}{\sqrt{\partial_\varepsilon G(u_\varepsilon)^2 + |\nabla' G(u_\varepsilon)|^2}} \frac{|\nabla' G(u_\varepsilon)|}{\sqrt{\partial_\varepsilon G(u_\varepsilon)^2 + |\nabla' G(u_\varepsilon)|^2}} \]

\[ = \frac{1}{\sqrt{1 + |v_\varepsilon|^2}} |\nabla' G(u_\varepsilon)|. \tag{8.24} \]

Letting \(\tilde{\mu}_\varepsilon\) be as in (6.14) we get from (2.2), (6.16), and Theorem B.3 the existence of a function \(g \in L^2(\mu)\) such that (up to a subsequence)

\[ \lim_{\varepsilon \to 0} (\tilde{\mu}_\varepsilon, \sqrt{1 + |v_\varepsilon|^2}) = (\mu, g) \tag{8.25} \]

as measure-function pairs on \(\Omega_T\) with values in \(\mathbb{R}\).

Let \(\eta \in C_0^0(\Omega_T)\). Then

\[ \left| \int_{\Omega_T} \eta \sqrt{1 + |v_\varepsilon|^2} |\nabla G(u_\varepsilon)| \, dx \, dt - \int_{\Omega_T} \eta \sqrt{1 + |v_\varepsilon|^2} d\tilde{\mu}_\varepsilon \right| \]

\[ = \left| \int_{\Omega_T} \eta \sqrt{1 + |v_\varepsilon|^2} \left( \sqrt{\frac{2W(u_\varepsilon)}{\varepsilon}} - \sqrt{\varepsilon |\nabla u_\varepsilon|} \right) \sqrt{\varepsilon |\nabla u_\varepsilon|} \, dx \, dt \right| \]

\[ \leq \left( \int_{\Omega_T} \eta^2 (1 + |v_\varepsilon|^2) \varepsilon |\nabla u_\varepsilon|^2 \, dx \, dt \right)^{1/2} \left( \int_{\Omega_T} \frac{2W(u_\varepsilon)}{\varepsilon} - \sqrt{\varepsilon |\nabla u_\varepsilon|} \right)^{1/2} \left| L^2(\Omega_T) \right| \]

\[ \leq \|\eta\|_{L^\infty (2TA_4 + A_3)^{1/2} (2|\xi|)(\Omega_T))^{1/2}. \tag{8.26} \]
Thanks to (8.25), (8.26) and (6.2) we conclude that
\[
\lim_{\varepsilon \to 0} (|\nabla G(u_\varepsilon)|L^{n+1}, \sqrt{1 + |v_\varepsilon|^2}) = (\mu, g)
\] (8.27)
as measure-function pairs on $\Omega_T$ with values in $\mathbb{R}$.

Again by (2.1) we have
\[
\int_{\{0 = |\nabla u_\varepsilon| < W(u_\varepsilon)\}} |\nabla' G(u_\varepsilon)| \, dx \, dt = \int_{\Omega_T} \eta |\nabla' G(u_\varepsilon)| \, dx \, dt \geq \frac{c_0}{2} \int_{\Omega_T} \eta |\nabla' u|,\]
where in the last inequality we have used the fact that $c_0 \geq \left(\frac{1}{2}\right)^{1/2} \Lambda_3 (\|\xi\|_{\Omega_T})^{1/2}$.

Considering now a set $B \subset \partial^* \{u = 1\}$ with $\mu(B) = 0$ we conclude that
\[
|\nabla' u|(B) \leq \frac{2}{c_0} \int_B g \, d\mu = 0,
\]
since $g \in L^2(\mu)$. \hfill \Box

**PROPOSITION 8.3** At $H^n$-almost all points in $\partial^* \{u = 1\}$ the tangential plane of $\mu$ exists.

**Proof.** The Radon–Nikodym theorem shows that the derivative
\[
f(z) := D_{|\nabla' u|} \mu(z) := \lim_{r \to 0} \frac{\mu(B_0^{n+1}(z))}{\mu(B_r^{n+1}(z))}
\] (8.28)
exists for $|\nabla' u|$-almost all $z \in \Omega_T$, and $f \in L^1(|\nabla' u|)$. By (8.15) we deduce that
\[
\mu(\partial^* \{u = 1\}) = f |\nabla' u|.
\] (8.29)

Similarly
\[
\frac{1}{f(z)} = D_{|\nabla' u|} |\nabla' u|(z)
\]
is finite for $\mu$-almost all $z \in \partial^* \{u = 1\}$. By (8.22) this implies that
\[
f > 0 \quad |\nabla' u|$-almost everywhere in $\Omega_T$. \hfill (8.30)

Since $|\nabla' u|$ is rectifiable and $f$ measurable with respect to $|\nabla' u|$ we find from (8.29), (8.30) and [31] Remark 11.5 that
\[
\mu(\partial^* \{u = 1\}) \text{ is rectifiable.} \hfill (8.31)
\]
Moreover, $\mathcal{H}^n$-almost all $z \in \partial^*[u = 1]$ satisfy
\[
\lim_{r \to 0} \frac{\mu(B_{r}^{n+1}(z) \setminus \partial^*[u = 1])}{\mu(B_{r}^{n+1}(z))} = 0, \quad (8.32)
\]
and
\[
\limsup_{r \to 0} \frac{\mu(B_{r}^{n+1}(z))}{\alpha_0 r^n} < \infty. \quad (8.33)
\]
In fact, (8.32) follows from \cite[Theorem 2.9.11]{[10]} and (8.22), and (8.33) from Proposition 8.1 and (8.22). Let now $z_0 \in \partial^*[u = 1]$ satisfy (8.32), (8.33). For an arbitrary $\eta \in C^1_c(\mathbb{B}_1^{n+1}(0))$ we then deduce that
\[
\limsup_{r \to 0} \left| \int_{\partial r \setminus \partial [u = 1]} \eta(r^{-1}(z - z_0)) r^{-n} \, d\mu(z) \right| \leq \|\eta\|_{C^1_c(\mathbb{B}_1^{n+1}(0))} \limsup_{r \to 0} \frac{\mu(B_{r}^{n+1}(z_0) \setminus \partial^*[u = 1])}{\mu(B_{r}^{n+1}(z_0))} \limsup_{r \to 0} \frac{\mu(B_{r}^{n+1}(z_0))}{\alpha_0 r^n} = 0
\]
by (8.32), (8.33). Therefore
\[
\lim_{r \to 0} \int_{\partial r} \eta(r^{-1}(z - z_0)) r^{-n} \, d\mu(z) = \lim_{r \to 0} \int_{\partial^*[u = 1]} \eta(r^{-1}(z - z_0)) r^{-n} \, d\mu(z)
\]
if the latter limit exists. By (8.31) we therefore conclude that at $\mathcal{H}^n$-almost all points of $\partial^*[u = 1]$ the tangential plane of $\mu$ exists and coincides with the tangential plane of $\mu \lfloor \partial^*[u = 1]$. \hfill \Box

**Proof of Proposition 4.5** Since $u \in BV(\Omega_T)$ and $u(t, \cdot) \in BV(\Omega)$ for almost all $t \in (0, T)$, we know that $\partial_t u$, $\nabla u$ are Radon measures on $\Omega_T$ and that $\nabla u(t, \cdot)$ is a Radon measure on $\Omega$ for almost all $t \in (0, T)$. Moreover we observe that $v \in L^1(|\nabla u|)$ since
\[
\int_{\Omega_T} |v| \, d|\nabla u| \leq \int_{\Omega_T} |v| \, d|\nabla' u| \leq \frac{2}{c_0} \int_{\Omega_T} g |v| \, d\mu \leq \frac{2}{c_0} \|g\|_{L^2(\mu)} \|v\|_{L^2(\mu)} < \infty
\]
by Theorem 4.4 and Proposition 8.2. From (3.5) and Proposition 8.3 we deduce that for any $\eta \in C^1_c(\Omega_T)$,
\[
- \int_{\Omega_T} \eta \, d\partial_t u = \int_{\Omega_T} \eta v \, d\nabla u = \int_{\Omega_T} \eta v \cdot \nabla u \, d|\nabla u| = \int_0^T \int_{\Omega} \eta V \, d|\nabla u(t, \cdot)| \, dt,
\]
which proves (4.9). \hfill \Box

**9. Conclusions**

Theorem 4.6 suggests defining a generalized action functional $S$ in the class of $L^2$-flows by
\[
S(\mu) := \inf_v \int_{\Omega_T} |v - H|^2 \, d\mu + 4S_{\text{muc}}(\mu), \quad (9.1)
\]
where the infimum is taken over all generalized velocities $v$ for the evolution $(\mu^t)_{t \in (0, T)}$. In the class of $n$-rectifiable $L^2$-flows we have
\[
S(\mu) = \int_{\Omega_T} |v - H|^2 \, d\mu + 4S_{\text{muc}}(\mu), \quad (9.2)
\]
where $v$ is the unique normal velocity of $(\mu^t)_{t \in (0, T)}$ (see Proposition 3.3).
In the present section we compare the functional $S$ with the functional $S^0$ defined in [17] (see (1.2)) and discuss the implications of Theorem 4.6 on a full Gamma-convergence result for the action functional. For ease of exposition we focus in this section on the switching scenario.

**Assumption 9.1** Let $(u_\varepsilon)_{\varepsilon > 0}$ be a sequence of smooth functions $u_\varepsilon : \Omega_T \to \mathbb{R}$ with uniformly bounded action (A1), zero Neumann boundary data (A3), and assume that for all $\varepsilon > 0$,

$$u_\varepsilon(0, \cdot) = -1, \quad u_\varepsilon(T, \cdot) = 1 \text{ in } \Omega. \quad (9.3)$$

Following [17] we define the reduced action functional on the set $M \subset BV(\Omega_T; \{-1, 1\}) \cap L^\infty(0, T; BV(\Omega))$ such that

- for every $\psi \in C^1_c(\Omega)$ the function $t \mapsto \int_\Omega u(t, \cdot) \psi \, dx$ is absolutely continuous on $[0, T]$;

- $(\partial^*_\varepsilon \{u(t, \cdot) = 1\})_{t \in (0, T)}$ is up to countably many times given as a smooth evolution of hypersurfaces.

By Assumption 9.1 the functional $S^0_{nuc}$ can be rewritten as

$$S^0(\eta) := c_0 \int_0^T \int_{\Sigma_t} |v(t, x) - H(t, x)|^2 \, dH^{n-1}(x) \, dt + 4S^0_{nuc}(\eta), \quad (9.4)$$

$$S^0_{nuc}(\eta) := \sup_{\eta \in M} \left( \lim_{t \downarrow t_0} \frac{c_0}{2} |\nabla u(t, \cdot)(\psi) - \lim_{t \uparrow t_0} \frac{c_0}{2} |\nabla u(t, \cdot)(\psi) \right) \right) + \sup_{\psi} \lim_{t \downarrow 0} \frac{c_0}{2} |\nabla u(t, \cdot)(\psi), \quad (9.5)$$

where the sup is taken over all $\psi \in C^1_c(\Omega)$ with $0 \leq \psi \leq 1$.

In [17, Proposition 2.2] a (formal) proof of the limsup estimate was given for a subclass of ‘nice’ functions in $M$. Following the ideas of that proof, using the one-dimensional construction [17, Proposition 3.1], and a density argument we expect that the limsup estimate can be extended to the whole set $M$. We do not give a rigorous proof here but assume the limsup estimate in the following.

**Assumption 9.2** For all $u \in M$ there exists a sequence $(u_\varepsilon)_{\varepsilon > 0}$ that satisfies Assumption 9.1 such that

$$u = \lim_{\varepsilon \to 0} u_\varepsilon, \quad S^0(\eta) \geq \limsup_{\varepsilon \to 0} S_\varepsilon(u_\varepsilon). \quad (9.6)$$

The natural candidate for the Gamma-limit of $S_\varepsilon$ with respect to $L^1(\Omega_T)$ is the $L^1(\Omega_T)$-lower semicontinuous envelope of $S^0$,

$$\overline{S}(u) := \inf \{\liminf_{k \to \infty} S^0(u_k) : (u_k)_{k \in \mathbb{N}} \subset M, u_k \to u \text{ in } L^1(\Omega_T)\}. \quad (9.7)$$
9.1 Comparison of $S$ and $S^0$

If we associate with a function $u \in M$ the measure $|\nabla u|$ on $\Omega_T$ we can compare $S^0(u)$ and $S(\frac{c_0}{2}|\nabla u|)$.

**Proposition 9.3** Let $u \in M$ and let $\mu = \mathcal{L}^1 \otimes \mu^t$ be an $L^2$-flow of measures. Assume that for almost all $t \in (0, T)$,

$$\mu^t \geq \frac{c_0}{2}|\nabla u(t, \cdot)|,$$

and the nucleation cost $S^0_{\text{nuc}}(u)$ is not larger than the nucleation cost $S_{\text{nuc}}(\mu)$. Then

$$S^0(u) \leq S(\mu).$$

For $\mu = \frac{c_0}{2}|\nabla u|$ we obtain

$$S^0(u) = S\left(\frac{c_0}{2}|\nabla u|\right).$$

**Proof.** The locality of the mean curvature [29] shows that the weak mean curvature of $\mu^t$ and the (classical) mean curvature coincide on $\partial\{u(t, \cdot) = 1\}$. By Proposition 4.5 any generalized velocity $v$ and the (classical) normal velocity $V$ are equal on the phase boundary. This shows that the integral part of $S^0(u)$ is not larger than the integral part of $S(\mu)$, with equality if $\mu^t = \frac{c_0}{2}|\nabla u(t, \cdot)|$ for almost all $t \in (0, T)$. This proves (9.9). For the measure $\frac{c_0}{2}|\nabla u|$ we observe that the nucleation cost $S_{\text{nuc}}(\frac{c_0}{2}\mu)$ equals the nucleation cost $S^0_{\text{nuc}}(u)$ and we obtain (9.10). \square

![Fig. 1. The phases $[u = 1]$.](image1)

![Fig. 2. The measure $\mu$.](image2)

If higher multiplicities occur for the measure $\mu$, the nucleation costs of $\mu$ and $u$ may differ and the value of $S^0(u)$ might be larger than $S(\mu)$, as the following example shows. Let $\Omega = (0, L)$, let $\{u = 1\}$ be the shaded regions in Figure 1 and let $\mu$ be the measure supported on the phase boundary and with double density on a hidden boundary connecting the upper and lower parts of the phase $\{u = 1\}$ (see Figure 2). At time $t_2$ a new phase is nucleated, but this time is not singular with respect to the evolution $(\mu^t)_{t \in (0,T)}$. On the other hand, no propagation cost occurs for the evolution $(u(t, \cdot))_{t \in (t_1,t_2)}$ whereas there is a propagation cost for $(\mu^t)_{t \in (t_1,t_2)}$. The difference in action is given by

$$S^0(u) - S(\mu) = 8c_0 - 2c_0\frac{(x_2 - x_1)^2}{t_2 - t_1}.$$
where \( x_1 \) is the annihilation point at time \( t_1 \) and \( x_2 \) the nucleation point at time \( t_2 \) (see Figure 1). This shows that as soon as \( x_2 - x_1 < 4\sqrt{t_2 - t_1} \) we have

\[
S(\mu) < S^0(u).
\]

The same example with \( x_2 = x_1 \) shows that \( S^0 \) is not lower semicontinuous and that a relaxation is necessary in order to obtain the Gamma-limit of \( S_\epsilon \). In fact, consider a sequence \((u_k)_{k \in \mathbb{N}}\) with phases \( \{u_k = 1\} \) given by the shaded region in Figure 3. Assume that the neck connecting the upper and lower parts of the shaded region disappears as \( k \to \infty \) and that \( u_k \) converges to the phase indicator function \( u \) with phase \( \{u = 1\} \) indicated by the shaded regions in Figure 4. Then a nucleation cost at time \( t_2 \) appears for \( u \). For the approximations \( u_k \) however there is no nucleation cost for \( t > 0 \) and the approximation can be made such that the propagation cost in \((t_1, t_2)\) is arbitrarily small, which shows that

\[
S^0(u) > \liminf_{k \to \infty} S^0(u_k).
\]

The situation in higher space dimensions is even more involved than in the one-dimensional examples discussed above. For instance one could create a circle with double density (no new phase is created) at a time \( t_1 \) and let this double-density circle grow until a time \( t_2 > t_1 \) where the circle splits and two circles evolve in different directions, one of them shrinking and the other growing. In this way a new phase is created at time \( t_2 \). In this example \( S \) counts the creation of a double-density circle at time \( t_1 \) and the cost of propagating that circle between the times \( t_1, t_2 \). In contrast, \( S^0 \) counts the nucleation cost of the new phase at time \( t_2 \), which is larger than the nucleation cost \( S_{\text{nuc}} \) at time \( t_1 \), but no propagation cost between the times \( t_1, t_2 \).

The analysis in [17] suggests that minimizers of the action functional exhibit nucleation and annihilation of phases only at the initial and final times. This class is therefore particularly interesting.

**Theorem 9.4** Let \((u_\varepsilon)_{\varepsilon > 0}\) satisfy Assumption 9.1 and suppose that Assumption 9.2 holds. Suppose that \( u_\varepsilon \to u \) in \( L^1(\Omega_T) \), \( u \in \mathcal{M} \), and \( u \) exhibits nucleation and annihilation of phases only at the final and initial times. Then

\[
\mathcal{S}(u) = S^0(u) \leq \liminf_{\varepsilon \to 0} S_\varepsilon(u_\varepsilon).
\]
In particular, $S_\varepsilon$ Gamma-converges to $S^0$ for those evolutions in $\mathcal{M}$ that have nucleations only at the initial time.

**Proof.** From the definition of the functional $\overline{S}$ we deduce that

$$\overline{S}(u) \leq S^0(u)$$

(9.12)

and there exists a sequence $(u_k)_{k \in \mathbb{N}} \subset \mathcal{M}$ such that

$$u = \lim_{k \to \infty} u_k, \quad \overline{S}(u) = \lim_{k \to \infty} S^0(u_k).$$

Assumption 9.2 implies that for all $k \in \mathbb{N}$ there exists a sequence $(u_{\varepsilon,k})_{\varepsilon > 0}$ such that

$$u_k = \lim_{\varepsilon \to 0} u_{\varepsilon,k}, \quad S^0(u_k) \geq \limsup_{\varepsilon \to 0} S_\varepsilon(u_{\varepsilon,k}).$$

(9.13)

Therefore we can choose a diagonal sequence $(u_{\varepsilon(k),k})_{k \in \mathbb{N}}$ such that

$$\overline{S}(u) \geq \limsup_{k \to \infty} S_\varepsilon(u_{\varepsilon(k),k}).$$

(9.14)

By Propositions 4.1 and 4.2 there exists a subsequence $k \to \infty$ such that

$$u_{\varepsilon(k),k} \to u, \quad \mu_{\varepsilon(k),k} \to \mu, \quad \mu \geq \frac{c_0}{2} |\nabla u|,$$

(9.15)

where the last inequality follows from

$$\frac{c_0}{2} \int_\Omega \eta \, d|\nabla u(t, \cdot)| \leq \liminf_{\varepsilon \to 0} \int_\Omega \eta |\nabla G(u_\varepsilon)| \, dx \leq \liminf_{\varepsilon \to 0} \int_\Omega \eta \, d\mu_\varepsilon = \int_\Omega \eta \, d\tilde{\mu},$$

with $G$ as in (8.23). By Theorem 4.6 we further deduce that

$$\liminf_{k \to \infty} S_\varepsilon(u) \geq S(\mu).$$

This implies by (9.14) that

$$\overline{S}(u) \geq S(\mu).$$

(9.16)

Since $\mu^0 = 0$ and $\mu^\varepsilon \geq \frac{c_0}{2} |\nabla u(t, \cdot)|$ the nucleation cost of $\mu$ at $t = 0$ is not lower than the nucleation cost for $u$. Since by assumption there are no more nucleation times we can apply Proposition 9.3 to obtain $S^0(u) \leq S(\mu)$. By (9.12), (9.16) we conclude that $S^0(u) = \overline{S}(u) = S(\mu)$.

Applying Proposition 4.1 and Theorem 4.6 to the sequence $(u_\varepsilon)_{\varepsilon > 0}$ we deduce that there exists a subsequence $\varepsilon \to 0$ such that

$$\mu_\varepsilon \to \tilde{\mu}, \quad \tilde{\mu} \geq \frac{c_0}{2} |\nabla u|$$

(9.17)

and

$$\liminf_{\varepsilon \to 0} S_\varepsilon(u_\varepsilon) \geq S(\tilde{\mu}).$$

Repeating the arguments above we deduce from Proposition 9.3 that $S^0(u) \leq S(\tilde{\mu})$ and

$$S^0(u) \leq \liminf_{\varepsilon \to 0} S_\varepsilon(u_\varepsilon).$$

Combining the upper bound (9.6) with (9.11) proves the Gamma-convergence of $S_\varepsilon$ in $u$. □
9.2 Gamma-convergence under an additional assumption

Using Theorem 4.6 we can prove the Gamma-convergence of $S_\varepsilon$ under an additional assumption on the structure of the set of those measures that arise as limits of sequences with uniformly bounded action.

**Assumption 9.5** Consider any sequence $(u_\varepsilon)_{\varepsilon > 0}$ with $u_\varepsilon \to u$ in $L^1(\Omega_T)$ that satisfies Assumption 9.1. Define the energy measures $\mu_\varepsilon$ according to (2.3) and let $\mu$ be any Radon measure such that for a subsequence $\varepsilon \to 0$,

$$\mu = \lim_{\varepsilon \to 0} \mu_\varepsilon.$$  \hfill (9.18)

Then we assume that there exists a sequence $(u_k)_{k \in \mathbb{N}} \subset \mathcal{M}$ such that

$$u = \lim_{k \to \infty} u_k, \quad S(\mu) \geq \lim_{k \to \infty} S^0(u_k).$$  \hfill (9.19)

For any $u \in \mathcal{M}$ that exhibits nucleation and annihilation only at initial and final times Assumption 9.5 is always satisfied: The proof of Theorem 9.4 and our results in Section 4 show that for any limit $\mu$ as in (9.18) we can apply Proposition 9.3. Therefore

$$S(u) \leq S(\mu)$$

and the constant sequence $u$ satisfies (9.19). However, a characterization of those $u \in \mathcal{M}$ such that Assumption 9.5 holds is open.

**Theorem 9.6** Suppose that Assumptions 9.1, 9.2 and 9.5 hold. Then

$$S_\varepsilon \to \overline{S} \quad \text{as } \varepsilon \to 0$$  \hfill (9.20)

in the sense of Gamma-convergence with respect to $L^1(\Omega_T)$.

**Proof.** We first prove the limsup estimate for $S_\varepsilon, \overline{S}$. In fact, fix an arbitrary $u \in L^1(\Omega_T; \{-1, 1\})$ with $\overline{S}(u) < \infty$. We deduce that there exists a sequence $(u_k)_{k \in \mathbb{N}}$ as in (9.7) such that

$$\overline{S}(u) = \lim_{k \to \infty} S^0(u_k).$$  \hfill (9.21)

By (9.6) for all $k \in \mathbb{N}$ there exists a sequence $(u_{\varepsilon,k})_{\varepsilon > 0}$ such that

$$\lim_{\varepsilon \to 0} u_{\varepsilon,k} = u_k, \quad S^0(u_k) \geq \limsup_{\varepsilon \to 0} S_\varepsilon(u_{\varepsilon,k}).$$

Choosing a suitable diagonal sequence $u_{\varepsilon(k),k}$ we deduce that

$$\overline{S}(u) \geq \lim_{k \to \infty} S_{\varepsilon(k)}(u_{\varepsilon(k),k}),$$  \hfill (9.22)

which proves the limsup estimate.

We next prove the liminf estimate. Consider an arbitrary sequence $(u_\varepsilon)_{\varepsilon > 0}$ that satisfies Assumption 9.1. By Theorem 4.6 there exists $u \in BV(\Omega_T; \{-1, 1\})$ and a measure $\mu$ on $\Omega_T$ such that

$$u_\varepsilon \to u \quad \text{in } L^1(\Omega_T), \quad \mu_\varepsilon \to \mu$$  \hfill (9.23)

for a subsequence $\varepsilon \to 0$, and

$$\liminf_{\varepsilon \to 0} S_\varepsilon(u_\varepsilon) \geq S(\mu).$$  \hfill (9.24)
By Assumption 9.5 there exists a sequence \((u_k)_{k \in \mathbb{N}} \subset \mathcal{M}\) such that (9.19) holds. By (9.24) and the definition of \(\mathcal{S}\) this yields
\[
\liminf_{\varepsilon \to 0} S_\varepsilon(u_\varepsilon) \geq S(\mu) \geq \lim_{k \to \infty} S^0(u_k) \geq \mathcal{S}(\mu)
\]
and proves the liminf estimate.

### Appendix A. Rectifiable measures and weak mean curvature

We briefly summarize some definitions from geometric measure theory. We always restrict ourselves to the hypersurface case, that is, ‘tangential plane’ and ‘rectifiability’ of a measure in \(\mathbb{R}^d\) means ‘\((d - 1)\)-dimensional tangential plane’ and ‘\((d - 1)\)-rectifiable’.

**Definition A.1** Let \(\mu\) be a Radon measure in \(\mathbb{R}^d\), \(d \in \mathbb{N}\).

1. We say that \(\mu\) has a (generalized) tangential plane at \(z \in \mathbb{R}^d\) if there exist a number \(\Theta > 0\) and a \((d - 1)\)-dimensional linear subspace \(T \subset \mathbb{R}^d\) such that
\[
\lim_{r \to 0} r^{-d+1} \int \eta \left( \frac{y - z}{r} \right) \, d\mu(y) = \Theta \int_T \eta \, d\mathcal{H}^{d-1} \quad \text{for every } \eta \in C_0^\infty(\mathbb{R}^d).
\]
We then set \(T_z \mu := T\) and call \(\Theta\) the multiplicity of \(\mu\) in \(z\).

2. If for \(\mu\)-almost all \(z \in \mathbb{R}^d\) a tangential plane exists then we call \(\mu\) rectifiable. If in addition the multiplicity is integer-valued \(\mu\)-almost everywhere we say that \(\mu\) is integer-rectifiable.

3. The first variation \(\delta \mu : C^1_c(\mathbb{R}^d, \mathbb{R}^d)\) of a rectifiable Radon-measure \(\mu\) on \(\mathbb{R}^d\) is defined by
\[
\delta \mu(\eta) := \int \text{div}_{T_z \mu} \eta \, d\mu.
\]
If there exists a function \(H \in L^1_{\text{loc}}(\mu)\) such that
\[
\delta \mu(\eta) = - \int H \cdot \eta \, d\mu
\]
we call \(H\) the weak mean-curvature vector of \(\mu\).

### Appendix B. Measure-function pairs

We recall some basic facts about the notion of measure-function pairs introduced by Hutchinson in [15].

**Definition B.1** Let \(E \subset \mathbb{R}^d\) be an open subset. Let \(\mu\) be a positive Radon measure on \(E\). Suppose \(f : E \to \mathbb{R}^m\) is well defined \(\mu\)-almost everywhere, and \(f \in L^1(\mu, \mathbb{R}^m)\). Then we say \((\mu, f)\) is a measure-function pair over \(E\) (with values in \(\mathbb{R}^m\)).

Next we define two notions of convergence for a sequence of measure-function pairs on \(E\) with values in \(\mathbb{R}^m\).
DEFINITION B.2 Suppose \( \{(\mu_k, f_k)\}_k \) and \( (\mu, f) \) are measure-function pairs over \( E \) with values in \( \mathbb{R}^m \). Suppose

\[
\lim_{k \to \infty} \mu_k = \mu
\]
as Radon measures on \( E \). Then we say \( (\mu_k, f_k) \) converges to \( (\mu, f) \) in the weak sense (in \( E \)) and write

\[
(\mu_k, f_k) \to (\mu, f),
\]
if \( \mu_k \lfloor f_k \to \mu \lfloor f \) in the sense of vector-valued measures, that is,

\[
\lim_{k \to \infty} \int f_k \cdot \eta \, d\mu_k = \int f \cdot \eta \, d\mu
\]
for all \( \eta \in C^0_c(E, \mathbb{R}^m) \).

The following result is a slightly less general version of [15, Theorem 4.4.2], sufficient for our aims.

THEOREM B.3 Let \( F : \mathbb{R}^m \to [0, \infty) \) be a continuous, convex function with superlinear growth at infinity, that is,

\[
\lim_{|y| \to \infty} \frac{F(y)}{|y|} = \infty.
\]

Let \( \{(\mu_k, f_k)\}_k \) be measure-function pairs over \( E \subset \mathbb{R}^d \) with values in \( \mathbb{R}^m \). Suppose \( \mu \) is a Radon measure on \( E \) and \( \mu_k \to \mu \) as \( k \to \infty \). Then the following are true:

1. If

\[
\sup_k \int f_k \, d\mu_k < \infty \quad (B1)
\]

then some subsequence of \( \{(\mu_k, f_k)\}_k \) converges in the weak sense to some measure-function pair \( (\mu, f) \) for some \( f \).

2. If \( (B1) \) holds and \( (\mu_k, f_k) \to (\mu, f) \) then

\[
\liminf_{k \to \infty} \int F(f_k) \, d\mu_k \geq \int F(f) \, d\mu \quad (B2)
\]

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