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ON MEASURE SOLUTIONS OF THE BOLTZMANN EQUATION PART I: MOMENT PRODUCTION AND STABILITY ESTIMATES

XUGUANG LU AND CLÉMENT MOUHOT

ABSTRACT. The spatially homogeneous Boltzmann equation with hard potentials is considered for measure valued initial data having finite mass and energy. Moment production estimates in the usual form and in the exponential form are obtained for measure solutions with and without angular cutoff on the collision kernel. For the Grad angular cutoff, it is also established the strong stability estimate for measure solutions.

Mathematics Subject Classification (2000): 35Q Equations of mathematical physics and other areas of application [See also 35J05, 35J10, 35K05, 35L05], 76P05 Rarefied gas flows, Boltzmann equation [See also 82B40, 82C40, 82D05].

Keywords: Boltzmann equation; spatially homogeneous; measure solution; moment estimate; moment production; exponential moment; stability estimate; Mehler transform.

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1. INTRODUCTION

In this paper we study the spatially homogeneous Boltzmann equation for **hard** interaction potentials with or without angular cutoff. The initial data are assumed to be positive Borel measures having finite moments up to order 2. Our main results are

the existence and stability of measure solutions that have polynomial and exponential moment production properties.

1.1. The spatially homogeneous Boltzmann equation. Before introducing the main results, let us recall the Boltzmann equation for L^1 solutions and basic notations. The equation for the space homogeneous solution takes the form

$$(1.1) \quad \frac{\partial}{\partial t} f_t(v) = Q(f_t, f_t)(v), \quad (v, t) \in \mathbb{R}^N \times (0, \infty), \quad N \geq 2$$

with some given initial data $f_t(v)|_{t=0} = f_0(v)$ and Q is the collision integral defined by

$$(1.2) \quad Q(f, f)(v) = \iint_{\mathbb{R}^N \times \mathbb{S}^{N-1}} B(v - v_*, \sigma) \left(f(v') f(v'_*) - f(v) f(v_*) \right) d\sigma dv_*,$$

where v, v_* and v', v'_* stand for velocities of two particles respectively after and before their collision,

$$v' = \frac{v + v_*}{2} + \frac{|v - v_*|}{2} \sigma, \quad v'_* = \frac{v + v_*}{2} - \frac{|v - v_*|}{2} \sigma, \quad \sigma \in \mathbb{S}^N.$$

The above relation between v, v_* and v', v'_* shows that the collision is elastic:

$$v' + v'_* = v + v_*, \quad |v'|^2 + |v'_*|^2 = |v|^2 + |v_*|^2.$$

The collision kernel $B(z, \sigma)$ is in general assumed to take the form

$$(1.3) \quad B(z, \sigma) = \bar{B}(|z|, \cos \theta), \quad \cos \theta = \frac{z}{|z|} \cdot \sigma, \quad \theta \in [0, \pi]$$

where $(r, \theta) \mapsto \bar{B}(r, \theta)$ is a nonnegative Borel function on $[0, \infty) \times [-1, 1]$ satisfying

$$(1.4) \quad \forall t \in (-1, 1), \quad r \mapsto \bar{B}(r, t) \text{ is continuous on } [0, \infty),$$

$$(1.5) \quad B(z, \sigma) \leq (1 + |z|^2)^{\gamma/2} b(\cos \theta), \quad \gamma > 0.$$

In this paper most of the results are concerned with the production form:

$$(1.6) \quad B(z, \sigma) = |z|^\gamma b(\cos \theta), \quad \gamma \in (0, 2].$$

Recall that this case corresponds to the so-called hard potential molecular interactions.

The angular function $b(\cdot)$ is a nonnegative Borel function on $[-1, 1]$ satisfying some weighted integrability. Our strongest assumption is that $b(\cdot)$ as a function of σ is integrable on the sphere \mathbb{S}^{N-1} , which means

$$\int_0^\pi b(\cos \theta) \sin^{N-2} \theta d\theta < \infty.$$

However more singular situations can be considered. The minimal assumption is that $b(\cdot) \sin^2 \theta$ is integrable on the sphere as a function of σ (this corresponds physically to an angular momentum), which means

$$\int_0^\pi b(\cos \theta) \sin^N \theta d\theta < \infty.$$

In the physical case, $N = 3$, it is well-known that for the hard sphere model, $b(\cdot) \equiv \text{cst.}$, whereas for hard potential model without angular cutoff, there is only weighted integrability:

$$\int_0^\pi b(\cos \theta) \sin \theta \, d\theta = \infty, \quad \int_0^\pi b(\cos \theta) \sin^2 \theta \, d\theta < \infty.$$

In this paper we consider the following different assumptions:

$$0 < \gamma \leq 2, \quad A_2 := |\mathbb{S}^{N-2}| \int_0^\pi b(\cos \theta) \sin^N \theta \, d\theta < \infty. \quad (\text{H0})$$

$$0 < \gamma \leq 2, \quad \int_0^\pi b(\cos \theta) \sin^N \theta (1 + |\log(\sin \theta)|) \, d\theta < \infty. \quad (\text{H1})$$

$$1 < \gamma < 2, \quad \int_0^\pi b(\cos \theta) \sin^{N-2+\beta} \theta \, d\theta < \infty, \quad \beta = 2 \left(\frac{2}{\gamma} - 1 \right) \in (0, 2). \quad (\text{H2})$$

$$\gamma = 2, \quad \exists p \in (1, \infty) \text{ s. t. } \int_0^\pi [b(\cos \theta)]^p \sin^{N-2} \theta \, d\theta < \infty. \quad (\text{H3})$$

$$0 < \gamma \leq 2, \quad A_0 := |\mathbb{S}^{N-2}| \int_0^\pi b(\cos \theta) \sin^{N-2} \theta \, d\theta < \infty. \quad (\text{H4})$$

Note that (H3)-(H4) corresponds to the angular ‘‘cutoff’’ case (short-range interactions), whereas (H0)-(H1)-(H2) allow for non locally integrable $b(\cdot)$ on the sphere, i.e. ‘‘non-cutoff’’ case (long-range interactions).

For any $\mathbf{n} \in \mathbb{S}^N$, let

$$\mathbb{S}^{N-2}(\mathbf{n}) = \{\omega \in \mathbb{S}^N \mid \omega \cdot \mathbf{n} = 0\} \quad (N \geq 3)$$

and in dimension $N = 2$ let

$$\mathbb{S}^0(\mathbf{n}) = \{-\mathbf{n}^\perp, \mathbf{n}^\perp\} \quad \text{where } \mathbf{n}^\perp \in \mathbb{S}^1 \text{ satisfies } \mathbf{n}^\perp \cdot \mathbf{n} = 0.$$

Then for any $g \in L^1(\mathbb{S}^N)$ or $g \geq 0$ (measurable) on \mathbb{S}^N we have

$$\int_{\mathbb{S}^N} g(\sigma) \, d\sigma = \int_0^\pi \sin^{N-2} \theta \left(\int_{\mathbb{S}^{N-2}(\mathbf{n})} g(\cos \theta \mathbf{n} + \sin \theta \omega) \, d\omega \right) \, d\theta$$

where $d\omega$ is the Lebesgue spherical measure on $\mathbb{S}^{N-2}(\mathbf{n})$ and in case $N = 2$ we define

$$\int_{\mathbb{S}^0(\mathbf{n})} g(\omega) \, d\omega = g(-\mathbf{n}^\perp) + g(\mathbf{n}^\perp).$$

Let $|\mathbb{S}^{N-2}(\mathbf{n})| = \int_{\mathbb{S}^{N-2}(\mathbf{n})} d\omega$, etc. Then $|\mathbb{S}^{N-2}(\mathbf{n})| = |\mathbb{S}^{N-2}|$ for $N \geq 3$, $|\mathbb{S}^0(\mathbf{n})| = |\mathbb{S}^0| = 2$ for $N = 2$.

By classical calculation one has

$$(1.7) \quad \langle Q(f, g), \varphi \rangle := \int_{\mathbb{R}^N} Q(f, g)(v) \varphi(v) \, dv = \frac{1}{2} \iint_{\mathbb{R}^N \times \mathbb{R}^N} L_B[\Delta \varphi](v, v_*) f(v) g(v_*) \, dv \, dv_*$$

where

$$\Delta \varphi = \Delta \varphi(v, v_*, v', v'_*) = \varphi(v') + \varphi(v'_*) - \varphi(v) - \varphi(v_*),$$

and

$$(1.8) \quad L_B[\Delta\varphi](v, v_*) = \int_0^\pi \bar{B}(|v - v_*|, \cos\theta) \sin^{N-2}\theta \left(\int_{\mathbb{S}^{N-2}(\mathbf{n})} \Delta\varphi \, d\omega \right) d\theta$$

and $\sigma = \cos\theta \mathbf{n} + \sin\theta \omega$, $\mathbf{n} = (v - v_*)/|v - v_*|$ for $v \neq v_*$; $\mathbf{n} = \mathbf{e}_1 = (1, 0, \dots, 0)$ for $v = v_*$.

Observe that when assuming (H0)-(H1)-(H2) (non locally integrable $b(\cdot)$), the collision operator in the dual form (1.7) above is well-defined thanks to the cancellations in the symmetric difference $\Delta\varphi$ of $\varphi \in C^2(\mathbb{R}^N)$. Basic estimates on $\Delta\varphi$ are as follows (see for instance [9, Lemma 3.2]): For all $(v, v_*, \sigma) \in \mathbb{R}^N \times \mathbb{R}^N \times \mathbb{S}^{N-1}$ one has

$$(1.9) \quad |\Delta\varphi| \leq \sqrt{2} \left(\max_{|u| \leq \sqrt{|v|^2 + |v_*|^2}} |\nabla\varphi(u)| \right) |v - v_*| \sin\theta;$$

$$(1.10) \quad \left| \int_{\mathbb{S}^{N-2}(\mathbf{n})} \Delta\varphi \, d\omega \right| \leq |\mathbb{S}^{N-2}| \left(\max_{|u| \leq \sqrt{|v|^2 + |v_*|^2}} |H_\varphi(u)| \right) |v - v_*|^2 \sin^2\theta,$$

where $\nabla\varphi$, H_φ are gradient and Hessian matrix of φ . Consequently the Boltzmann equation (1.1) in a weak form can be written

$$(1.11) \quad \int_{\mathbb{R}^N} \varphi(v) f_t(v) \, dv = \int_{\mathbb{R}^N} \varphi(v) f_0(v) \, dv + \int_0^t \langle Q(f_\tau, f_\tau), \varphi \rangle \, d\tau.$$

From the estimate (1.10) it is easily seen that if $A_2 < \infty$ (minimal assumption) then $L_B[\Delta\varphi]$ is well-defined for all $\varphi \in C^2(\mathbb{R}^N)$.

In fact we shall prove in Proposition 2.1 (see Section 2) that $(v, v_*) \mapsto L_B[\Delta\varphi](v, v_*)$ is also continuous on $\mathbb{R}^N \times \mathbb{R}^N$. Furthermore if

$$\int_0^\pi b(\cos\theta) \sin^{N-1}\theta \, d\theta < \infty$$

then from the estimate (1.9) one sees that

$$L_B[|\Delta\varphi|](v, v_*) = \int_{\mathbb{S}^N} B(v - v_*, \sigma) |\Delta\varphi| \, d\sigma < \infty$$

so that L_B coincides with the simpler formula

$$(1.12) \quad L_B[\Delta\varphi](v, v_*) = \int_{\mathbb{S}^N} B(v - v_*, \sigma) \Delta\varphi \, d\sigma.$$

The collision integral (1.7) and the equation (1.11) for L^1 -functions are naturally extended to finite Borel measures. For every $0 \leq s < \infty$, let $\mathcal{B}_s(\mathbb{R}^N) = (\mathcal{B}_s(\mathbb{R}^N), \|\cdot\|_s)$ be the Banach space of real Borel measures on \mathbb{R}^N having finite total variations up to order s , i.e.

$$\|\mu\|_s := \int_{\mathbb{R}^N} \langle v \rangle^s \, d|\mu|(v) < \infty, \quad \langle v \rangle := (1 + |v|^2)^{1/2}$$

where the positive Borel measure $|\mu|$ is the total variation of μ . In particular $\|\mu\| = \|\mu\|_0 = |\mu|(\mathbb{R}^N)$ is simply the total variation of μ . Let

$$\mathcal{B}_s^+(\mathbb{R}^N) = \{\mu \in \mathcal{B}_s(\mathbb{R}^N) \mid \mu \geq 0\}.$$

Let us denote

$$C_b^k(\mathbb{R}^N) = \left\{ \varphi \in C^k(\mathbb{R}^N) \mid \sum_{|\alpha| \leq k} \sup_{v \in \mathbb{R}^N} |\partial^\alpha \varphi(v)| < \infty \right\}.$$

Our test function space for defining measure weak solutions is then $C_b^2(\mathbb{R}^N)$.

Finally by analogy with $\mathcal{B}_s(\mathbb{R}^N)$ we introduce the class $L_{-s}^\infty(\mathbb{R}^N)$ of *locally bounded* Borel functions such that

$$\psi \in L_{-s}^\infty(\mathbb{R}^N) \iff \|\psi\|_{L_{-s}^\infty} := \sup_{v \in \mathbb{R}^N} |\psi(v)| \langle v \rangle^{-s} < \infty$$

and we define

$$L_{-s}^\infty \cap C^k(\mathbb{R}^N) = \left\{ \varphi \in C^k(\mathbb{R}^N) \mid \sum_{|\alpha| \leq k} \|\partial^\alpha \varphi\|_{L_{-s}^\infty} < \infty \right\}, \quad s \geq 0, \quad k \in \mathbb{N}.$$

In accordance with (1.7) we now define for every $\mu, \nu \in \mathcal{B}_s(\mathbb{R}^N)$ and every suitable smooth function φ

$$(1.13) \quad \langle Q(\mu, \nu), \varphi \rangle := \frac{1}{2} \iint_{\mathbb{R}^N \times \mathbb{R}^N} L_B[\Delta \varphi](v, v_*) d\mu(v) d\nu(v_*).$$

1.2. Previous results and references. Let us give a short (and non exhaustive) overview of the main previous results and references related to the subject of this paper.

Cauchy theory for the spatially homogeneous Boltzmann equation for hard potentials with cutoff. The first rigorous mathematical result is due to Carleman [7, 8] who proved existence and uniqueness of solutions in $L^1 \cap L^\infty$ with pointwise moment bounds, for hard spheres interactions. A general Cauchy theory was later developed by Arkeryd [3, 4] who proved existence and uniqueness of solutions in $L^1 \cap L \log L$ with L^1 moment bounds. More recently optimal results were obtained by Mischler and Wennberg [19] (see also Lu [17]), and we refer the references therein for a more extensive bibliography.

Cauchy theory for the spatially homogeneous Boltzmann equation for hard potentials without cutoff. This theory is much more recent, and not complete at now. As far as existence theory is concerned let us mention the seminal works of Villani [24] and then Alexandre and Villani [2]. As far as uniqueness results are concerned (in the general far from equilibrium regime), let us mention the works [23, 12, 14, 13] based on Wasserstein metrics and probabilistic tools, and the work [10] based on *a priori* estimates. Finally let us mention the related recent works in the *perturbative close-to-equilibrium regime* (but without assuming spatial homogeneity) of Gressman and Strain [16] on the one hand, and Alexandre, Morimoto, Ukai, Xu, Yang [1] on other hand.

Polynomial moment bounds. The first seminal result of the propagation of polynomial moments that exists initially for “variable hard spheres” (hard potentials with angular cutoff) is due to Elmroth [11] and makes use of so-called “Povzner’s inequalities” [21]. Then Desvillettes proved, for the same model, the appearance of any polynomial as

soon as a moment of order strictly higher than 2 exists initially (see also [25]). Finally optimal results were obtained in [19] again.

Exponential moment bounds The first seminal result of propagation of moments of exponential form is due to Bobylev [5], still in the case of short-ranged interactions. Improvements of these results were later obtained in [6]. Let us also mention the related result of propagation of pointwise maxwellian bound in [15]. Inspired by the same techniques, the appearance of exponential moments was first obtained by the second author together with Mischler in [20, 18].

1.3. Definition of Measure Weak Solutions.

Definition 1.1. Let $B(z, \sigma)$ be given by (1.3)-(1.4)-(1.5) with γ and $b(\cdot)$ satisfying (H0). Let $F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$ and $\{F_t\}_{t \geq 0} \subset \mathcal{B}_2^+(\mathbb{R}^N)$. We say that $\{F_t\}_{t \geq 0}$, or simply F_t , is a **measure weak solution** of Eq. (1.1) associated with the initial datum F_0 , if it satisfies the following:

(i) $\sup_{t \geq 0} \|F_t\|_2 < \infty$.

(ii) For every $\varphi \in C_b^2(\mathbb{R}^N)$,

$$\left\{ \begin{array}{l} \iint_{\mathbb{R}^N \times \mathbb{R}^N} |L_B[\Delta\varphi](v, v_*)| dF_t(v) dF_t(v_*) < \infty, \quad \forall t > 0 \\ t \mapsto \langle Q(F_t, F_t), \varphi \rangle \text{ belongs to } C((0, \infty)) \cap L_{\text{loc}}^1([0, \infty)) \\ \int_{\mathbb{R}^N} \varphi(v) dF_t(v) = \int_{\mathbb{R}^N} \varphi(v) dF_0(v) + \int_0^t \langle Q(F_\tau, F_\tau), \varphi \rangle d\tau \quad \forall t \geq 0. \end{array} \right.$$

Moreover a measure weak solution F_t is called a **conservative solution** if it conserves the mass, momentum and energy, i.e.

$$\int_{\mathbb{R}^N} \begin{pmatrix} 1 \\ v \\ |v|^2 \end{pmatrix} dF_t(v) = \int_{\mathbb{R}^N} \begin{pmatrix} 1 \\ v \\ |v|^2 \end{pmatrix} dF_0(v) \quad \forall t \geq 0.$$

Note that every measure weak solution conserves at least the mass.

Our first main result of the paper is the following

Theorem 1.2 (Existence of solutions and moment production estimates without cut-off). *Suppose that $B(z, \sigma) = |z|^\gamma b(\cos \theta)$ satisfies (H1). Given any initial datum $F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$ with $\|F_0\|_0 > 0$, we have*

- (a) *The Eq. (1.1) always has a conservative measure weak solution F_t , and the solution F_t can be chosen such as to satisfy the moment production estimate:*

$$(1.14) \quad \|F_t\|_s \leq \mathcal{K}_s(F_0) \left(1 + \frac{1}{t}\right)^{\frac{s-2}{\gamma}} \quad \forall t > 0, \quad \forall s \geq 2$$

where

$$(1.15) \quad \mathcal{K}_s(F_0) = \|F_0\|_2 \left(2^{s+7} \frac{\|F_0\|_2}{\|F_0\|_0} \left(1 + \frac{1}{16\|F_0\|_2 A_2 \gamma}\right)\right)^{\frac{s-2}{\gamma}}.$$

- (b) *If in addition either $0 < \gamma \leq 1$ or one of the assumptions (H2) or (H3) is satisfied, then every solution in part (a), or more generally every conservative measure weak solution F_t having the property of moment production*

$$\sup_{t \geq t_0} \|F_t\|_s < \infty \quad \forall t_0 > 0, \quad \forall s > 2,$$

satisfies a moment production estimate of exponential form:

$$(1.16) \quad \int_{\mathbb{R}^N} \exp(c(t)\langle v \rangle^\gamma) dF_t(v) \leq 2\|F_0\|_0 \quad \forall t > 0,$$

where

$$c(t) = 2^{-s_0} \frac{\|F_0\|_0}{\|F_0\|_2} (1 - e^{-\alpha t}), \quad \alpha = 16\|F_0\|_2 A_2 \gamma$$

and $1 < s_0 < \infty$ depends only on $b(\cdot)$ and γ .

Corollary 1.3. *Under the same assumptions on $B(z, \sigma)$ and the initial datum F_0 in Theorem 1.2, there exists a conservative measure weak solution F_t of Eq. (1.1) such that for any $0 < s < \gamma$ and any $R > 0$*

$$\int_{\mathbb{R}^N} \exp(R\langle v \rangle^s) dF_t(v) \leq (\exp(C_s(t)) + 2) \|F_0\|_0 \quad \forall t > 0$$

where

$$C_s(t) = R \left(\frac{R}{c(t)} \right)^{s/(\gamma-s)}.$$

Proof. The proof of this Corollary is quite short and we can present it here. As a consequence of Theorem 1.2 there exists a conservative measure weak solution F_t of Eq. (1.1) such that F_t satisfies (1.16). For any $t > 0$, if $R\langle v \rangle^s > C_s(t)$, then $\langle v \rangle^{\gamma-s} > (\frac{1}{R}C_s(t))^{\gamma-s/s} = \frac{R}{c(t)}$ and so

$$R\langle v \rangle^s = \frac{R}{c(t)\langle v \rangle^{\gamma-s}} c(t)\langle v \rangle^\gamma \leq c(t)\langle v \rangle^\gamma.$$

Thus

$$\begin{aligned} \int_{\mathbb{R}^N} e^{R\langle v \rangle^s} dF_t(v) &= \int_{\{R\langle v \rangle^s \leq C_s(t)\}} e^{R\langle v \rangle^s} dF_t(v) + \int_{\{R\langle v \rangle^s > C_s(t)\}} e^{R\langle v \rangle^s} dF_t(v) \\ &\leq e^{C_s(t)} \|F_0\|_0 + \int_{\{R\langle v \rangle^s > C_s(t)\}} e^{c(t)\langle v \rangle^\gamma} dF_t(v) \leq e^{C_s(t)} \|F_0\|_0 + 2\|F_0\|_0. \end{aligned}$$

□

1.4. Definition of Measure Strong Solutions. Now let us consider **measure strong solutions** of Eq. (1.1) under the angular cutoff assumption (H4). Let $B(z, \sigma)$ be given by (1.3)-(1.4)-(1.5) with $b(\cdot)$ satisfying $A_2 < \infty$. Then we can define bilinear operators $Q^\pm : \mathcal{B}_{s+\gamma}(\mathbb{R}^N) \times \mathcal{B}_{s+\gamma}(\mathbb{R}^N) \rightarrow \mathcal{B}_s(\mathbb{R}^N)$ ($s \geq 0$) and

$$(1.17) \quad Q(\mu, \nu) := Q^+(\mu, \nu) - Q^-(\mu, \nu)$$

through Riesz's representation theorem by

$$(1.18) \quad \int_{\mathbb{R}^N} \psi(v) dQ^+(\mu, \nu)(v) = \iint_{\mathbb{R}^N \times \mathbb{R}^N} L_B[\psi](v, v_*) d\mu(v) d\nu(v_*),$$

$$(1.19) \quad \int_{\mathbb{R}^N} \psi(v) dQ^-(\mu, \nu)(v) = \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|) \psi(v) d\mu(v) d\nu(v_*)$$

for all $\psi \in L_{-s}^\infty \cap C^0(\mathbb{R}^N)$, where

$$(1.20) \quad L_B[\psi](v, v_*) = \int_{\mathbb{S}^N} B(v - v_*, \sigma) \psi(v') d\sigma, \quad A(|z|) = \int_{\mathbb{S}^{N-1}} B(z, \sigma) d\sigma$$

and recall that $\mathbf{n} = (v - v_*)/|v - v_*|$ in $b(\mathbf{n} \cdot \sigma)$ is replaced by a fixed unit vector \mathbf{e}_1 for $v = v_*$.

Recall that the norm $\|\mu\|_s$ of $\mu \in \mathcal{B}_s(\mathbb{R}^N)$ ($s \geq 0$) can be estimated in terms of compactly smooth test functions: For all $k \geq 0$

$$(1.21) \quad \|\mu\|_s = \sup_{\varphi \in C_c^k(\mathbb{R}^N), \|\varphi\|_{L_{-s}^\infty} \leq 1} \left| \int_{\mathbb{R}^N} \varphi d\mu \right|.$$

Basic properties of the Borel measures $Q^\pm(\mu, \nu)$ are as follows (which will be proven in Section 2):

Proposition 1.4. *Let $B(z, \sigma)$ be given by (1.3)-(1.4)-(1.5) with $b(\cdot)$ satisfying $A_0 < \infty$. Then*

$$Q^\pm : \mathcal{B}_{s+\gamma}(\mathbb{R}^N) \times \mathcal{B}_{s+\gamma}(\mathbb{R}^N) \rightarrow \mathcal{B}_s(\mathbb{R}^N) \quad (s \geq 0)$$

are bounded and

$$(1.22) \quad \|Q^\pm(\mu, \nu)\|_s \leq 2^{(s+\gamma)/2} A_0 (\|\mu\|_{s+\gamma} \|\nu\|_0 + \|\mu\|_0 \|\nu\|_{s+\gamma}),$$

$$(1.23) \quad \|Q^\pm(\mu, \mu) - Q^\pm(\nu, \nu)\|_s \leq 2^{(s+\gamma)/2} A_0 (\|\mu + \nu\|_{s+\gamma} \|\mu - \nu\|_0 + \|\mu + \nu\|_0 \|\mu - \nu\|_{s+\gamma})$$

and hence

$$(1.24) \quad \|Q(\mu, \mu) - Q(\nu, \nu)\|_0 \leq 2^{1+(s+\gamma)/2} A_0 (\|\mu + \nu\|_\gamma \|\mu - \nu\|_0 + \|\mu + \nu\|_0 \|\mu - \nu\|_\gamma).$$

Finally for all $\mu \in \mathcal{B}_\gamma(\mathbb{R}^N)$ and all $\varphi \in C_b^2(\mathbb{R}^N)$, there holds

$$(1.25) \quad \langle Q(\mu, \mu), \varphi \rangle = \int_{\mathbb{R}^N} \varphi dQ(\mu, \mu)$$

where the left-hand side of (1.25) is defined in (1.13).

Definition 1.5. Let $B(z, \sigma)$ be given by (1.3)-(1.4)-(1.5) with γ and $b(\cdot)$ satisfying (H4). Let $F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$ and $\{F_t\}_{t \geq 0} \subset \mathcal{B}_2^+(\mathbb{R}^N)$. We say that F_t is a measure strong solution of Eq.(1.1) associated with the initial datum $F_t|_{t=0} = F_0$, if it satisfies the following:

- (i) $\sup_{t \geq 0} \|F_t\|_2 < \infty$.

(ii) $t \mapsto F_t \in C([0, \infty); \mathcal{B}_2(\mathbb{R}^N)) \cap C^1([0, \infty); \mathcal{B}_0(\mathbb{R}^N))$ and

$$(1.26) \quad \frac{d}{dt}F_t = Q(F_t, F_t), \quad t \in [0, \infty).$$

Note from (1.22)-(1.23)-(1.24) that the strong continuity of

$$t \mapsto F_t \in C([0, \infty); \mathcal{B}_2(\mathbb{R}^N))$$

implies the strong continuity $t \mapsto Q(F_t, F_t) \in C([0, \infty); \mathcal{B}_0(\mathbb{R}^N))$, so that the differential equation (1.26) is equivalent to

$$(1.27) \quad F_t = F_0 + \int_0^t Q(F_s, F_s)ds, \quad t \geq 0$$

where the integral is taken in the Riemann sense or generally in the Bochner sense. Recall also that here the derivative $\frac{d}{dt}\mu_t$ and integral $\int_a^b \nu_t dt$ as measures are defined by

$$\left(\frac{d}{dt}\mu_t\right)(E) = \frac{d}{dt}\mu_t(E), \quad \left(\int_a^b \nu_t dt\right)(E) = \int_a^b \nu_t(E)dt$$

for all Borel sets $E \subset \mathbb{R}^N$.

Note also that if a strong measure solution F_t is absolutely continuous with respect to the Lebesgue measure for all $t \geq 0$, i.e. $dF_t = f_t dv$, then it is easily seen that f_t (after modification on a v -null set) is a mild solution of Eq. (1.1). That is, $(t, v) \mapsto f_t(v)$ is nonnegative and Lebesgue measurable on $[0, \infty) \times \mathbb{R}^N$ and for every $t \geq 0$, $v \mapsto f_t(v)$ belongs to $L^1_2(\mathbb{R}^N)$, $\sup_{t \geq 0} \|f_t\|_{L^1_2} < \infty$, and there is a Lebesgue null set $Z_0 \subset \mathbb{R}^N$ (which is independent of t) such that

$$(1.28) \quad \begin{cases} \int_0^t Q^\pm(f_\tau, f_\tau)(v)d\tau < \infty \quad \forall t \in [0, \infty), \quad \forall v \in \mathbb{R}^N \setminus Z_0 \\ f_t(v) = f_0(v) + \int_0^t Q(f_\tau, f_\tau)(v)d\tau, \quad \forall t \in [0, \infty), \quad \forall v \in \mathbb{R}^N \setminus Z_0. \end{cases}$$

Here

$$L^1_s(\mathbb{R}^N) = \left\{ f \in L^1(\mathbb{R}^N) \mid \|f\|_{L^1_s} := \int_{\mathbb{R}^N} |f(v)| \langle v \rangle^s dv < \infty \right\}, \quad s \geq 0.$$

From classical measure theory [22, Theorem 6.13, page 149]: if $d\mu = f dv$ for $f \in L^1_s(\mathbb{R}^N)$, then $d|\mu| = |f| dv$ and hence $\|\mu\|_s = \|f\|_{L^1_s}$.

For any positive measure $\mu \in \mathcal{B}_2^+(\mathbb{R}^N)$ we introduce the following continuous function $r \mapsto \Psi_\mu(r)$ on $[0, \infty)$:

$$(1.29) \quad \Psi_\mu(r) = r + r^{1/3} + \int_{|v| > r^{-1/3}} |v|^2 d\mu(v), \quad r > 0; \quad \Psi_\mu(0) = 0.$$

Our second main result of this paper is

Theorem 1.6 (Uniqueness and stability estimates for locally integrable b). *Let $B(z, \sigma) = |z|^\gamma b(\cos \theta)$ satisfy (H4). Then*

- (a) *Every conservative measure weak solution of Eq. (1.1) is a strong solution, while every measure strong solution of Eq. (1.1) is a measure weak solution.*

- (b) Let F_t be a measure strong solution of Eq. (1.1) with initial datum F_0 satisfying $\|F_t\|_2 \leq \|F_0\|_2$ for all $t \geq 0$. Then F_t in fact conserves the mass, momentum and energy.
- (c) Given any $F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$. There exists a unique conservative measure strong solution F_t of Eq. (1.1) such that $F_t|_{t=0} = F_0$. Therefore if $\|F_0\|_0 > 0$, then F_t satisfies the moment production estimates in Theorem 1.2 .
- (d) Let F_t be a conservative measure strong solutions of Eq. (1.1) with an initial datum $F_t|_{t=0} = F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$, and suppose $\|F_0\|_0 > 0$. Let G_t be a conservative measure strong solutions of Eq. (1.1) with time-interval (τ, ∞) with an initial datum $G_t|_{t=\tau} = G_\tau \in \mathcal{B}_2^+(\mathbb{R}^N)$ for some $\tau \geq 0$. Then:

– If $\tau = 0$, then

$$(1.30) \quad \|F_t - G_t\|_2 \leq \Psi_{F_0}(\|F_0 - G_0\|_2)e^{C(1+t)}, \quad t \geq 0$$

where Ψ_{F_0} is given by (1.29), $C = \mathcal{R}(\gamma, A_0, A_2 \|F_0\|_0, \|F_0\|_2)$ is an explicit positive continuous function on $(\mathbb{R}_+)^{\otimes 5}$.

– If $\tau > 0$, then

$$(1.31) \quad \|F_t - G_t\|_2 \leq \|F_\tau - G_\tau\|_2 e^{c_\tau(t-\tau)}, \quad t \in [\tau, \infty)$$

where $c_\tau = 4A_0(\mathcal{K}_{2+\gamma}(F_0) + \|F_0\|_2)(1 + \frac{1}{\tau})$, $\mathcal{K}_{2+\gamma}(F_0)$ is given in (1.15) with $s = 2 + \gamma$.

- (e) If $F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$ is absolutely continuous with respect to the Lebesgue measure, i.e. $dF_0 = f_0 dv$ with $0 \leq f_0 \in L_2^1(\mathbb{R}^N)$, then the unique conservative measure strong F_t with the initial datum F_0 is also absolutely continuous with respect to the Lebesgue measure: $dF_t = f_t dv$ for all $t \geq 0$, and f_t is the unique conservative mild solution of Eq. (1.1) with the initial datum f_0 .
- (f) If $F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$ is not a Dirac-mass and let F_t be the unique measure strong solution of Eq. (1.1) with initial datum F_0 , then there is a sequence $\{f_t^n\}$ of conservative L^1 -solutions of Eq. (1.1) with initial data $0 \leq f_0^n \in L_2^1(\mathbb{R}^N)$ satisfying

$$(1.32) \quad \int_{\mathbb{R}^N} \begin{pmatrix} 1 \\ v \\ |v|^2 \end{pmatrix} f_0^n(v) dv = \int_{\mathbb{R}^N} \begin{pmatrix} 1 \\ v \\ |v|^2 \end{pmatrix} dF_0(v), \quad n = 1, 2, \dots$$

such that

$$(1.33) \quad \lim_{n \rightarrow \infty} \int_{\mathbb{R}^N} \varphi(v) f_t^n(v) dv = \int_{\mathbb{R}^N} \varphi(v) dF_t(v) \quad \forall \varphi \in C_b(\mathbb{R}^N), \quad \forall t \geq 0.$$

Remark 1.7. An application of the estimate (1.31) for solutions with different initial times will be seen in our next paper concerning the rate of convergence to equilibrium.

Remark 1.8. In the second part of this work we shall prove the exponential convergence to equilibrium (for bounded angular function $b(\cdot)$): $\|F_t - M\|_0 \leq Ce^{-ct}$ where M is the Maxwellian (gaussian) with the same mass, momentum and energy as F_0 (assuming that F_0 is not a single Dirac mass and $\|F_0\|_0 > 0$), $C, c > 0$ are constants depending only on $N, b(\cdot), \gamma$ and the mass, momentum and energy of F_0 . This results shall allow to prove that the stability estimate (1.30) can be improved to be uniform in time:

$$\sup_{t \geq 0} \|F_t - G_t\|_2 \leq \tilde{\Psi}_{F_0}(\|F_0 - G_0\|_2)$$

for some explicit continuous function $\tilde{\Psi}_{F_0}(r)$ on $[0, \infty)$ satisfying $\tilde{\Psi}_{F_0}(0) = 0$.

2. CONTINUITY AND CONVERGENCE

We shall prove in this section the continuity of the collision kernel. It is required for defining measure weak solutions of Eq. (1.1) as we mentioned in Section 1, but also for proving weak convergence of approximate solutions, which leads to the existence of measure weak solutions.

2.1. Representations of $\langle v \rangle^2, \langle v'_* \rangle^2$. We first begin this section with a preliminary technical computation.

For any $v, v_* \in \mathbb{R}^N$, let us define

$$\mathbf{h} = \frac{v + v_*}{|v + v_*|} \quad \text{for } v + v_* \neq 0; \quad \mathbf{h} = \mathbf{e}_1 = (1, 0, \dots, 0) \quad \text{for } v + v_* = 0$$

and recall that $\mathbf{n} = (v - v_*)/|v - v_*|$ when $v \neq v_*$ and $\mathbf{n} = \mathbf{e}_1$ else. By definition

$$(2.1) \quad \begin{cases} \langle v' \rangle^2 := 1 + |v'|^2 = \frac{\langle v \rangle^2 + \langle v_* \rangle^2}{2} + \frac{|v + v_*||v - v_*|}{2}(\mathbf{h} \cdot \sigma) \\ \langle v'_* \rangle^2 := 1 + |v'_*|^2 = \frac{\langle v \rangle^2 + \langle v_* \rangle^2}{2} - \frac{|v + v_*||v - v_*|}{2}(\mathbf{h} \cdot \sigma). \end{cases}$$

Let us also define the unit vector

$$\mathbf{j} = \frac{\mathbf{h} - (\mathbf{h} \cdot \mathbf{n})\mathbf{n}}{\sqrt{1 - (\mathbf{h} \cdot \mathbf{n})^2}} \quad \text{for } |\mathbf{h} \cdot \mathbf{n}| < 1 \quad \text{and } \mathbf{j} = \mathbf{e}_1 \quad \text{for } |\mathbf{h} \cdot \mathbf{n}| = 1.$$

Then with the change of variables $\sigma = \cos \theta \mathbf{n} + \sin \theta \omega$, $\omega \in \mathbb{S}^{N-2}(\mathbf{n})$, we have

$$\mathbf{h} \cdot \sigma = (\mathbf{h} \cdot \mathbf{n}) \cos \theta + \sqrt{1 - (\mathbf{h} \cdot \mathbf{n})^2} \sin \theta (\mathbf{j} \cdot \omega), \quad \omega \in \mathbb{S}^{N-2}(\mathbf{n})$$

so that we get another representation:

$$(2.2) \quad \begin{cases} \langle v' \rangle^2 = \langle v \rangle^2 \cos^2 \theta / 2 + \langle v_* \rangle^2 \sin^2 \theta / 2 + \sqrt{|v|^2 |v_*|^2 - (v \cdot v_*)^2} \sin \theta (\mathbf{j} \cdot \omega) \\ \langle v'_* \rangle^2 = \langle v \rangle^2 \sin^2 \theta / 2 + \langle v_* \rangle^2 \cos^2 \theta / 2 - \sqrt{|v|^2 |v_*|^2 - (v \cdot v_*)^2} \sin \theta (\mathbf{j} \cdot \omega). \end{cases}$$

2.2. Continuity of the collision kernel. Let us now prove the continuity property.

Proposition 2.1. *Let $B(z, \sigma)$ be given by (1.3)-(1.4)-(1.5) with $b(\cdot)$ satisfying $A_2 < \infty$. Then*

(I) *The function $(v, v_*) \mapsto L_B[\Delta \varphi](v, v_*)$ is continuous on $\mathbb{R}^N \times \mathbb{R}^N$ for all $\varphi \in C^2(\mathbb{R}^N)$.*

(II) *Let $B_n(z, \sigma) = \bar{B}_n(|z|, \cos \theta)$ satisfy (1.4) and*

$$(2.3) \quad \bar{B}_n(r, t) \nearrow \bar{B}(r, t) \quad (n \rightarrow \infty) \quad \forall (r, t) \in [0, \infty) \times (-1, 1).$$

Then for any $\varphi \in C^2(\mathbb{R}^N)$ and any $0 < R < \infty$

$$(2.4) \quad \sup_{|v|+|v_*| \leq R} |L_{B_n}[\Delta \varphi](v, v_*) - L_B[\Delta \varphi](v, v_*)| \rightarrow 0 \quad (n \rightarrow \infty).$$

Moreover let $\varphi_n \in C^2(\mathbb{R}^N)$ satisfy

$$(2.5) \quad \lim_{n \rightarrow \infty} \varphi_n(v) = \varphi(v) \quad \forall v \in \mathbb{R}^N; \quad \sup_{n \geq 1} \sup_{|v| \leq R} \sum_{|\alpha| \leq 2} |\partial^\alpha \varphi_n(v)| < \infty \quad \forall R < \infty.$$

Then

$$(2.6) \quad L_{B_n}[\Delta \varphi_n](v, v_*) \rightarrow L_B[\Delta \varphi](v, v_*) \quad (n \rightarrow \infty) \quad \forall (v, v_*) \in \mathbb{R}^N \times \mathbb{R}^N.$$

Proof. Let us write

$$(2.7) \quad L_B[\Delta \varphi](v, v_*) = \int_0^\pi \bar{B}(|v - v_*|, \cos \theta) \sin^N \theta L[\Delta \varphi](v, v_*, \theta) d\theta$$

where

$$L[\Delta \varphi](v, v_*, \theta) = \frac{1}{\sin^2 \theta} \int_{\mathbb{S}^{N-2}(\mathbf{n})} \Delta \varphi \, d\omega, \quad 0 < \theta < \pi.$$

Recalling (1.10) we have

$$(2.8) \quad \sup_{0 < \theta < \pi} |L[\Delta \varphi](v, v_*, \theta)| \leq |\mathbb{S}^{N-2}| \left(\max_{|u| \leq \sqrt{|v|^2 + |v_*|^2}} |H_\varphi(u)| \right) |v - v_*|^2.$$

Part (I). For any $0 < R < \infty$, consider decomposition

$$B(v - v_*, \sigma) = B(v - v_*, \sigma) \wedge R + (B(v - v_*, \sigma) - R)^+$$

where $x \wedge y = \min\{x, y\}$, $(x - y)^+ = \max\{x - y, 0\}$. We have

$$\begin{aligned} L_B[\Delta \varphi](v, v_*) &= L_{B \wedge R}[\Delta \varphi](v, v_*) + L_{(B-R)^+}[\Delta \varphi](v, v_*), \\ L_{B \wedge R}[\Delta \varphi](v, v_*) &= \int_{\mathbb{S}^{N-1}} [B(v - v_*, \sigma) \wedge R] \Delta \varphi \, d\sigma. \end{aligned}$$

Fix any $(v_0, v_{*0}) \in \mathbb{R}^N \times \mathbb{R}^N$. Applying (2.7)-(2.8) to $L_{(B-R)^+}[\Delta \varphi]$ and recalling the assumption (1.5) we have

$$\sup_{|v-v_0|^2 + |v_*-v_{*0}|^2 \leq 1} |L_{(B-R)^+}[\Delta \varphi](v, v_*)| \leq C_\varphi \int_0^\pi \left(C_\gamma b(\cos \theta) - R \right)^+ \sin^N \theta d\theta =: I_{\varphi, \gamma}(R)$$

where C_φ, C_γ are finite constants depending only on $\varphi, \gamma, v_0, v_{*0}$. Therefore

$$(2.9) \quad \begin{aligned} &|L_B[\Delta \varphi](v, v_*) - L_B[\Delta \varphi](v_0, v_{*0})| \\ &\leq |L_{B \wedge R}[\Delta \varphi](v, v_*) - L_{B \wedge R}[\Delta \varphi](v_0, v_{*0})| + I_{\varphi, \gamma}(R) \quad \forall |v - v_0|^2 + |v_* - v_{*0}|^2 \leq 1. \end{aligned}$$

Let $(\Delta \varphi)_0 = \varphi(v_0') + \varphi(v_{*0}') - \varphi(v_0) - \varphi(v_{*0})$. Applying (2.7) to $L_{B \wedge R}[\Delta \varphi]$ and using the assumption (1.4) we have

$$\begin{aligned} &|L_{B \wedge R}[\Delta \varphi](v, v_*) - L_{B \wedge R}[\Delta \varphi](v_0, v_{*0})| \\ &\leq C_\varphi |\mathbb{S}^{N-2}| \int_0^\pi \left| \bar{B}(|v - v_*|, \cos \theta) \wedge R - \bar{B}(|v_0 - v_{*0}|, \cos \theta) \wedge R \right| \sin^{N-2} \theta d\theta \\ &+ R \int_{\mathbb{S}^{N-1}} \left| \Delta \varphi - (\Delta \varphi)_0 \right| d\sigma \rightarrow 0 \quad \text{as } (v, v_*) \rightarrow (v_0, v_{*0}). \end{aligned}$$

Also by assumption $\int_0^\pi b(\cos \theta) \sin^N \theta d\theta < \infty$ we have $I_{\varphi, \gamma}(R) \rightarrow 0$ as $R \rightarrow +\infty$. Thus from (2.9), by first letting $(v, v_*) \rightarrow (v_0, v_{*0})$ and then letting $R \rightarrow +\infty$, we obtain

$$\limsup_{(v, v_*) \rightarrow (v_0, v_{*0})} |L_B[\Delta\varphi](v, v_*) - L_B[\Delta\varphi](v_0, v_{*0})| = 0.$$

Part (II). By assumption (2.3) and (1.5) we have $\bar{B}_n(r, \cos \theta) \leq \bar{B}_{n+1}(r, \cos \theta) \leq \bar{B}(r, \cos \theta) \leq (1 + r^2)^{\gamma/2} b(\cos \theta)$ which together with (1.4) implies that the functions

$$r \mapsto \int_0^\pi \bar{B}_n(r, \cos \theta) \sin^N \theta d\theta, \quad r \mapsto \int_0^\pi \bar{B}(r, \cos \theta) \sin^N \theta d\theta$$

are all continuous on $[0, \infty)$. Thus by first using (2.3) and dominated convergence and then using Dini's theorem we conclude that for any $0 < R < \infty$

$$\int_0^\pi \left(\bar{B}(r, \cos \theta) - \bar{B}_n(r, \cos \theta) \right) \sin^N \theta d\theta \rightarrow 0 \quad (n \rightarrow \infty) \text{ uniformly in } r \in [0, R].$$

Therefore applying (2.7)-(2.8) to $L_{B-B_n}[\Delta\varphi]$ we have, for any $0 < R < \infty$,

$$\begin{aligned} \sup_{|v|+|v_*| \leq R} |L_B[\Delta\varphi](v, v_*) - L_{B_n}[\Delta\varphi](v, v_*)| &= \sup_{|v|+|v_*| \leq R} |L_{B-B_n}[\Delta\varphi](v, v_*)| \\ &\leq C_{\varphi, R} \sup_{r \in [0, R]} \int_0^\pi \left(\bar{B}(r, \cos \theta) - \bar{B}_n(r, \cos \theta) \right) \sin^N \theta d\theta \rightarrow 0 \quad (n \rightarrow \infty) \end{aligned}$$

where $C_{\varphi, R} = \sup_{|u| \leq R} |H_\varphi(u)| R^2$.

Finally for any $(v, v_*) \in \mathbf{R}^N \times \mathbf{R}^N$, using (2.5) and denoting $r = |v - v_*|$ we have by dominated convergence that

$$\begin{aligned} |L_B[\Delta\varphi](v, v_*) - L_{B_n}[\Delta\varphi_n](v, v_*)| &\leq |L_B[\Delta(\varphi - \varphi_n)](v, v_*)| + |L_{B-B_n}[\Delta\varphi_n](v, v_*)| \\ &\leq \int_0^\pi \bar{B}(r, \cos \theta) \sin^N \theta |L[\Delta(\varphi - \varphi_n)](v, v_*, \theta)| d\theta \\ &+ C \int_0^\pi \left(\bar{B}(r, \cos \theta) - \bar{B}_n(r, \cos \theta) \right) \sin^N \theta d\theta \rightarrow 0 \quad (n \rightarrow \infty). \end{aligned}$$

□

Proposition 2.2. *Let $0 \leq s_j < \infty$, $\{\mu_j^n\}_{n=1}^\infty \subset \mathcal{B}_{s_j}^+(\mathbb{R}^{N_j})$, $\mu_j \in \mathcal{B}_0^+(\mathbb{R}^{N_j})$ satisfy*

$$(2.10) \quad \sup_{n \geq 1} \|\mu_j^n\|_{s_j} < \infty, \quad j = 1, 2, \dots, k;$$

$$(2.11) \quad \lim_{n \rightarrow \infty} \int_{\mathbb{R}^{N_j}} \varphi_j d\mu_j^n = \int_{\mathbb{R}^{N_j}} \varphi_j d\mu_j, \quad \forall \varphi_j \in C_c^\infty(\mathbb{R}^{N_j}), \quad j = 1, 2, \dots, k.$$

Then

$$(2.12) \quad \mu_j \in \mathcal{B}_{s_j}^+(\mathbb{R}^{N_j}), \quad \|\mu_j\|_{s_j} \leq \liminf_{n \rightarrow \infty} \|\mu_j^n\|_{s_j}, \quad j = 1, 2, \dots, k.$$

Moreover if $\Psi_n, \Psi \in C(\mathbb{R}^{N_1} \times \mathbb{R}^{N_2} \times \dots \times \mathbb{R}^{N_k})$ satisfy

$$(2.13) \quad \lim_{|\mathbf{x}| \rightarrow \infty} \sup_{n \geq 1} \frac{|\Psi_n(\mathbf{x})|}{\sum_{j=1}^k \langle x_j \rangle^{s_j}} = 0, \quad \lim_{n \rightarrow \infty} \sup_{|\mathbf{x}| \leq R} |\Psi_n(\mathbf{x}) - \Psi(\mathbf{x})| = 0$$

for all $0 < R < \infty$, where $\mathbf{x} = (x_1, x_2, \dots, x_k) \in \otimes_{j=1}^k \mathbb{R}^{N_j}$, then

$$(2.14) \quad \lim_{n \rightarrow \infty} \int_{\otimes_{j=1}^k \mathbb{R}^{N_j}} \Psi_n d(\mu_1^n \otimes \mu_2^n \otimes \dots \otimes \mu_k^n) = \int_{\otimes_{j=1}^k \mathbb{R}^{N_j}} \Psi d(\mu_1 \otimes \mu_2 \otimes \dots \otimes \mu_k).$$

Proof. First (2.12) easily follows from Fatou's Lemma. Let us prove (2.14). Consider

$$M = \sup_{n \geq 1} \{ \|\mu_1^n\|_{s_1}, \|\mu_2^n\|_{s_2}, \dots, \|\mu_k^n\|_{s_k} \}$$

and

$$\nu^n = \mu_1^n \otimes \mu_2^n \otimes \dots \otimes \mu_k^n, \quad \nu = \mu_1 \otimes \mu_2 \otimes \dots \otimes \mu_k.$$

By assumption on Ψ_n, Ψ , for any $\varepsilon > 0$ there exist $R > 0, n_\varepsilon \geq 1$ such that for all $n \geq n_\varepsilon$ one has

$$(2.15) \quad |\Psi_n(\mathbf{x})|, |\Psi(\mathbf{x})| < \varepsilon \sum_{j=1}^k \langle x_j \rangle^{s_j}, \quad \forall |\mathbf{x}| > R,$$

and

$$(2.16) \quad |\Psi_n(\mathbf{x}) - \Psi(\mathbf{x})| < \varepsilon, \quad \forall |\mathbf{x}| \leq k(R+2).$$

On the other hand, by polynomial approximation, there exists a polynomial $P(\mathbf{x})$ such that

$$(2.17) \quad |\Psi(\mathbf{x}) - P(\mathbf{x})| < \varepsilon \quad \forall |\mathbf{x}| \leq k(R+2).$$

Choose $\chi_j^R \in C_c^\infty(\mathbb{R}^{N_j})$ satisfying $0 \leq \chi_j^R(x_j) \leq 1$ on \mathbb{R}^{N_j} and $\chi_j^R(x_j) = 1$ for $|x_j| \leq R$ and $\chi_j^R(x_j) = 0$ for $|x_j| \geq R+2$. If we write $P(\mathbf{x}) = \sum_{i=0}^m \prod_{j=1}^k P_{i,j}(x_j)$ where $m \in \mathbb{N}$ and $P_{i,j}(x_j)$ are polynomials in x_j , then

$$P(\mathbf{x}) \prod_{j=1}^k \chi_j^R(x_j) = \sum_{i=0}^m \prod_{j=1}^k \varphi_{i,j}(x_j)$$

where $\varphi_{i,j}(x_j) = P_{i,j}(x_j) \chi_j^R(x_j)$, $i = 0, 1, 2, \dots, m, j = 1, 2, \dots, k$. Then consider the decomposition:

$$\begin{aligned} & \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \Psi_n d\nu^n - \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \Psi d\nu = \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \Psi_n \left(1 - \prod_{j=1}^k \chi_j^R\right) d\nu^n \\ & + \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} (\Psi_n - \Psi) \prod_{j=1}^k \chi_j^R d\nu^n + \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} (\Psi - P) \prod_{j=1}^k \chi_j^R d\nu^n \\ & + \left[\sum_{i=0}^m \prod_{j=1}^k \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \varphi_{i,j} d\mu_j^n - \sum_{i=0}^m \prod_{j=1}^k \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \varphi_{i,j} d\mu_j \right] \\ & + \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} (P - \Psi) \prod_{j=1}^k \chi_j^R d\nu + \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \Psi \left(\prod_{j=1}^k \chi_j^R - 1 \right) d\nu \\ & := I_{n,1} + I_{n,2} + I_{n,3} + I_{n,4} + I_5 + I_6. \end{aligned}$$

Since $1 - \prod_{j=1}^k \chi_j^R(x_j) = 0$ for all $|\mathbf{x}| \leq R$, and $\prod_{j=1}^k \chi_j^R(x_j) = 0$ for all $|\mathbf{x}| > k(R+2)$, it follows from (2.15)-(2.16)-(2.17) that for all $n \geq n_\varepsilon$

$$\begin{aligned} |I_{n,1}| + |I_6| &\leq 2\varepsilon \int_{|\mathbf{x}|>R} \sum_{j=1}^k \langle x_j \rangle^{s_j} d\nu^n \leq 2\varepsilon k M^k, \\ |I_{n,2}| + |I_{n,3}| + |I_5| &\leq 2\varepsilon \int_{|\mathbf{x}| \leq k(R+2)} d\nu^n + \varepsilon \int_{|\mathbf{x}| \leq k(R+2)} d\nu \leq 3\varepsilon M^k. \end{aligned}$$

For $I_{n,4}$, since $\varphi_{i,j} \in C_c^\infty(\mathbb{R}^{N_j})$, it follows from the assumption of the lemma that

$$I_{n,4} = \sum_{i=0}^m \left(\prod_{j=1}^k \int_{\mathbb{R}^{N_j}} \varphi_{i,j} d\mu_j^n - \prod_{j=1}^k \int_{\mathbb{R}^{N_j}} \varphi_{i,j} d\mu_j \right) \rightarrow 0 \quad (n \rightarrow \infty).$$

Therefore

$$\limsup_{n \rightarrow \infty} \left| \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \Psi_n d\nu^n - \int_{\prod_{j=1}^k \mathbb{R}^{N_j}} \Psi d\nu \right| \leq 5k M^k \varepsilon.$$

This proves (2.14) by letting $\varepsilon \rightarrow 0+$. \square

We end this section with the

Proof of Proposition 1.4. By elementary inequalities

$$\langle v' \rangle^s \leq (\langle v \rangle^2 + \langle v_* \rangle^2)^{s/2}, \quad (1 + |v - v_*|^2)^{\gamma/2} \leq 2^{\gamma/2} (\langle v \rangle^2 + \langle v_* \rangle^2)^{\gamma/2}$$

and the assumption on B we have for any $\varphi \in C_c(\mathbb{R}^N)$ with $\|\varphi\|_{L^\infty_s} \leq 1$

$$|\varphi(v')| B(v - v_*, \sigma) \leq \langle v' \rangle^s (1 + |v - v_*|^2)^{\gamma/2} b(\cos \theta) \leq 2^{(s+\gamma)/2} (\langle v \rangle^{s+\gamma} + \langle v_* \rangle^{s+\gamma}) b(\cos \theta)$$

and hence

$$\begin{aligned} \iint_{\mathbb{R}^N \times \mathbb{R}^N} L_B[|\varphi|](v, v_*) d(|\mu| \otimes |\nu|) &\leq A_0 2^{(s+\gamma)/2} (\|\mu\|_{s+\gamma} \|\nu\|_0 + \|\mu\|_0 \|\nu\|_{s+\gamma}), \\ \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|) |\varphi(v)| d(|\mu| \otimes |\nu|) &\leq A_0 2^{(s+\gamma)/2} (\|\mu\|_{s+\gamma} \|\nu\|_0 + \|\mu\|_0 \|\nu\|_{s+\gamma}). \end{aligned}$$

These imply (1.22). The inequality (1.23) follows from (1.22) and the following identities:

$$Q^\pm(\mu, \mu) - Q^\pm(\nu, \nu) = \frac{1}{2} Q^\pm(\mu + \nu, \mu - \nu) + \frac{1}{2} Q^\pm(\mu - \nu, \mu + \nu).$$

Next recall $B(v - v_*, \sigma) = \bar{B}(|v - v_*|, \frac{v - v_*}{|v - v_*|} \cdot \sigma)$. By changing variables $\sigma \rightarrow -\sigma$, $v \leftrightarrow v_*$ and using Fubini's theorem we have

$$\int_{\mathbb{R}^N} \varphi dQ^+(\mu, \mu) = \frac{1}{2} \iint_{\mathbb{R}^N \times \mathbb{R}^N} \left(\int_{\mathbf{S}^{N-1}} B(v - v_*, \sigma) (\varphi(v') + \varphi(v'_*)) d\sigma \right) d\mu(v) d\mu(v_*).$$

A similar symmetry for $\int_{\mathbb{R}^N} \varphi dQ^-(\mu, \mu)$ is obvious. The difference of the two is equal to $\langle Q(\mu, \mu), \varphi \rangle$. This proves (1.25). \square

3. SOME LEMMAS

In this section we collect and prove some inequalities that will be used to prove our main result.

Lemma 3.1 (Cf. [6]). *Let $p \geq 1$ and $k_p = [(p+1)/2]$ the integer part of $(p+1)/2$. Then for all $x, y \geq 0$*

$$\sum_{k=0}^{k_p-1} \binom{p}{k} (x^k y^{p-k} + x^{p-k} y^k) \leq (x+y)^p \leq \sum_{k=0}^{k_p} \binom{p}{k} (x^k y^{p-k} + x^{p-k} y^k)$$

where

$$\binom{p}{k} = \frac{p(p-1)\cdots(p-k+1)}{k!}, \quad k \geq 1; \quad \binom{p}{0} = 1.$$

Let $p \geq 1$ and $n \in \{1, 2, \dots, [p]\}$. Then using Taylor's formula for the function $x \mapsto (1+x)^p$ one has

$$\sum_{k=0}^n \binom{p}{k} x^k \leq (1+x)^p \quad \forall x \geq 0.$$

In particular

$$(3.1) \quad \sum_{k=0}^n \binom{p}{k} \leq 2^p, \quad 1 \leq n \leq p.$$

Let $\Gamma(x), B(x, y)$ be the gamma and beta functions:

$$\Gamma(x) = \int_0^\infty t^{x-1} e^{-t} dt, \quad x > 0; \quad B(x, y) = \int_0^1 t^{x-1} (1-t)^{y-1} dt, \quad x, y > 0.$$

It is well-known that

$$(3.2) \quad \Gamma(x)\Gamma(y) = \Gamma(x+y)B(x, y), \quad \forall x, y > 0.$$

Other relations that we shall also use are: For any integer $k \geq 1$ and for any real number $p \geq k$ we have

$$(3.3) \quad \binom{p}{k} = \frac{\Gamma(p+1)}{\Gamma(p-k+1)\Gamma(k+1)}.$$

And

$$(3.4) \quad B(x+1, y) + B(x, y+1) = B(x, y), \quad x, y > 0.$$

Lemma 3.2. *Let $0 < \alpha, \eta < \infty$, $g \in C([0, \eta])$ and $S \in C^1([0, \eta])$ such that*

$$S(0) = 0, \quad S'(x) < 0 \quad \forall x \in [0, \eta].$$

Then for any $\lambda \geq 1$ we have

$$\int_0^\eta x^{\alpha-1} g(x) e^{\lambda S(x)} dx = \Gamma(\alpha) \left(\frac{1}{-\lambda S'(0)} \right)^\alpha (g(0) + o(1))$$

where $o(1) \rightarrow 0$ as $\lambda \rightarrow \infty$.

Proof. This is classical stationary phase type of analysis, we omit the proof for the sake of conciseness of this paper. \square

Lemma 3.3. *Let $p \geq 3$ and $k_p = \lfloor (p+1)/2 \rfloor$. Then*

$$(3.5) \quad \sum_{k=1}^{k_p} \binom{p}{k} B(k, p-k) \leq 4 \log p.$$

More generally for any $a > 1$ we have

$$(3.6) \quad \sum_{k=1}^{k_p} \binom{p}{k} B(ak, a(p-k)) \leq C_a (ap)^{1-a},$$

$$(3.7) \quad \sum_{k=0}^{k_p-1} \binom{p-2}{k} B(a(k+1), a(p-k-1)) \leq C_a (ap)^{-a}$$

where $0 < C_a < \infty$ only depends on a .

Proof. Since $p \geq 3$ we have

$$\sum_{k=1}^{k_p} \binom{p}{k} B(k, p-k) = \sum_{k=1}^{k_p} \frac{p}{k(p-k)} = \sum_{k=1}^{k_p} \left(\frac{1}{k} + \frac{1}{p-k} \right) \leq 2 \sum_{k=1}^{k_p} \frac{1}{k} \leq 4 \log p.$$

Now suppose $a > 1$. Let

$$\sum_{k=1}^{k_p} \binom{p}{k} B(ak, a(p-k)) = I_a(p) + I_a(p, k_p)$$

where

$$I_a(p) = \sum_{k=1}^{k_p-1} \binom{p}{k} B(ak, a(p-k))$$

and

$$I_a(p, k_p) = \binom{p}{k_p} B(ak_p, a(p-k_p)).$$

For the first term $I_a(p)$ we use the symmetry (w.r.t $x = 1/2$) and Lemma 3.1 to get

$$\begin{aligned} I_a(p) &:= \sum_{k=1}^{k_p-1} \binom{p}{k} B(ak, a(p-k)) \\ &= \frac{1}{2} \int_0^1 \frac{1}{x(1-x)} \left\{ \sum_{k=1}^{k_p-1} \binom{p}{k} \left(x^{ak}(1-x)^{a(p-k)} + x^{a(p-k)}(1-x)^{ak} \right) \right\} dx \\ &\leq \frac{1}{2} \int_0^1 \frac{1}{x(1-x)} \left\{ \left(x^a + (1-x)^a \right)^p - x^{ap} - (1-x)^{ap} \right\} dx \\ &= \int_0^{1/2} \frac{1}{x(1-x)} \left\{ \left(x^a + (1-x)^a \right)^p - x^{ap} - (1-x)^{ap} \right\} dx. \end{aligned}$$

Omitting the negative term $-x^{ap}$ we have

$$(x^a + (1-x)^a)^p - x^{ap} - (1-x)^{ap} \leq p(x^a + (1-x)^a)^{p-1}x^a$$

so that

$$I_a(p) \leq p \int_0^{1/2} x^{a-1} g_1(x) e^{pS(x)} dx$$

where $g_1(x) = (1-x)^{-1}(x^a + (1-x)^a)^{-1}$ and $S(x) = \log(x^a + (1-x)^a)$, $x \in [0, 1/2]$. Since $g_1(0) = 1$, $S(0) = 0$ and

$$S'(0) = -a, \quad S'(x) = \frac{a(x^{a-1} - (1-x)^{a-1})}{x^a + (1-x)^a} < 0 \quad \forall x \in [0, 1/2]$$

(because $a > 1$) it follows from Lemma 3.2 that for all $p \geq 3$

$$I_a(p) \leq C_a p \Gamma(a) \left(\frac{1}{pa}\right)^a = C_a (ap)^{1-a}.$$

For the second term $I_a(p, k_p)$ we use Stirling's formula

$$\Gamma(x) = \left(\frac{x}{e}\right)^x \sqrt{\frac{2\pi}{x}} e^{\frac{\theta_x}{12x}}, \quad \Gamma(x+1) = x\Gamma(x) = \left(\frac{x}{e}\right)^x \sqrt{2\pi x} e^{\frac{\theta_x}{12x}}, \quad x \geq 1$$

($0 < \theta_x < 1$) to compute

$$(3.8) \quad I_a(p, k_p) = \frac{\Gamma(p+1)}{\Gamma(k_p+1)\Gamma(p-k_p+1)} \cdot \frac{\Gamma(ak_p)\Gamma(a(p-k_p))}{\Gamma(ap)} \\ \leq e^{1/4} \frac{\sqrt{a}}{ap} \left(\frac{k_p}{p}\right)^{(a-1)k_p} \left(\frac{p-k_p}{p}\right)^{(a-1)(p-k_p)} \left(\frac{p}{k_p}\right) \left(\frac{p}{p-k_p}\right) \leq C_a \frac{1}{ap} \left(\frac{1}{2}\right)^{(a-1)p}.$$

Here in the last inequality we used the simple estimates

$$\frac{p-1}{2} \leq p - k_p \leq \frac{p+1}{2}$$

for $p \geq 3$. This proves (3.6) because $a > 1$.

In order to prove (3.7) we consider again a decomposition

$$\sum_{k=0}^{k_p-1} \binom{p-2}{k} B(a(k+1), a(p-k-1)) = J_a(p) + J_a(p, k_p)$$

where for the first term $J_a(p)$ we use that $k_p - 2 = [(p-1)/2] - 1 = k_{p-2} - 1$ and Lemma 3.1 to get

$$J_a(p) = \sum_{k=0}^{k_p-2} \binom{p-2}{k} B(a(k+1), a(p-k-1)) \\ = \frac{1}{2} \int_0^1 x^{a-1} (1-x)^{a-1} \sum_{k=0}^{k_p-2-1} \binom{p-2}{k} \left(x^{ak} (1-x)^{a(p-2-k)} + x^{a(p-2-k)} (1-x)^{ak} \right) dx \\ \leq \frac{1}{2} \int_0^1 x^{a-1} (1-x)^{a-1} \left(x^a + (1-x)^a \right)^{p-2} dx = \int_0^{1/2} x^{a-1} g_2(x) e^{pS(x)} dx$$

with $g_2(x) = (1-x)^{a-1}(x^a + (1-x)^a)^{-2}$. Since $a > 1$, it follows from Lemma 3.2 that

$$J_a(p) \leq C_a \left(\frac{1}{ap} \right)^a.$$

For the second term $J_a(p, k_p)$ we use (3.8) to get

$$J_a(p, k_p) := \binom{p-2}{k_p-1} B(ak_p, a(p-k_p)) = \frac{(p-k_p)k_p}{p(p-1)} I_a(p, k_p) \leq C_a \frac{1}{ap} \left(\frac{1}{2} \right)^{(a-1)p}.$$

Since $a > 1$, this proves the lemma. \square

Lemma 3.4. *Suppose $b(\cdot)$ satisfies the assumption (H0). For all $p \geq 3$ we define*

$$(3.9) \quad \varepsilon_p := \frac{2}{A_2} |\mathbb{S}^{N-2}| \int_0^\pi b(\cos \theta) \sin^N \theta \int_0^1 t \left(1 - \frac{\sin^2 \theta}{2} t \right)^{p-2} dt d\theta \quad (\leq 1).$$

Then $\varepsilon_p \rightarrow 0$ ($p \rightarrow \infty$). Furthermore, if either $0 < \gamma \leq 1$ or (H2) is satisfied, then

$$(3.10) \quad p^{2-\frac{2}{\gamma}} \varepsilon_p \rightarrow 0 \quad (p \rightarrow \infty).$$

Proof. Under the assumption (H0), the convergence $\varepsilon_p \rightarrow 0$ ($p \rightarrow \infty$) is obvious. And if $0 < \gamma \leq 1$ then $2/\gamma \geq 2$, and so (3.10) is also trivial. Suppose (H2) is satisfied. Then $1 < \gamma < 2$ and $\beta = 2(2/\gamma - 1) \in (0, 2)$. Let $\nu = 1 - \beta/2$. Then for all $p \geq 4$

$$(3.11) \quad \begin{aligned} \varepsilon_p p^\nu &\leq 2^\nu \varepsilon_p (p-2)^\nu \\ &\leq C_{\nu, N, A_2} \int_0^\pi b(\cos \theta) \sin^{N-2\nu} \theta \int_0^1 \left((p-2) \frac{\sin^2 \theta}{2} t \right)^\nu \left(1 - \frac{\sin^2 \theta}{2} t \right)^{p-2} dt d\theta. \end{aligned}$$

From the elementary estimates

$$0 \leq (kx)^\nu (1-x)^k < 1, \quad (kx)^\nu (1-x)^k \rightarrow 0 \quad (k \rightarrow \infty) \quad \forall x \in [0, 1]$$

we get, setting $k = p-2$, $x = t \sin^2 \theta / 2$, that

$$\left((p-2) \frac{\sin^2 \theta}{2} t \right)^\nu \left(1 - \frac{\sin^2 \theta}{2} t \right)^{p-2} \rightarrow 0 \quad (p \rightarrow \infty)$$

for all $\theta \in [0, \pi]$ and $t \in [0, 1]$. Since by assumption (H2), $\theta \mapsto b(\cos \theta) \sin^{N-2\nu} \theta = b(\cos \theta) \sin^{N-2+\beta} \theta$ is integrable on $[0, \pi]$, it follows from (3.11) and the dominated convergence theorem that $\varepsilon_p p^\nu \rightarrow 0$ ($p \rightarrow \infty$). \square

Remark 3.5. It is easily calculated that if $A_0 < \infty$, then $\varepsilon_p \leq (16A_0)/(A_2 p)$ for all $p \geq 3$, so that in case $0 < \gamma < 2$ we have $p^{2-2/\gamma} \varepsilon_p \leq (16A_0 p^{1-2/\gamma})/A_2$.

Lemma 3.6. *Let $B(z, \sigma) = |z|^\gamma b(\cos \theta)$.*

(I) Under the assumption (H0) we have for all $p \geq 3$

$$\begin{aligned}
(3.12) \quad & L_B [\Delta \langle \cdot \rangle^{2p}] (v, v_*) \\
& \leq -\frac{A_2}{4} \left(\langle v \rangle^{2p+\gamma} + \langle v_* \rangle^{2p+\gamma} \right) + \frac{A_2}{2} \left(\langle v \rangle^{2p} \langle v_* \rangle^\gamma + \langle v_* \rangle^{2p} \langle v \rangle^\gamma \right) \\
& + A_2 \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k+\gamma} \langle v_* \rangle^{2(p-k)} + \langle v \rangle^{2(p-k)+\gamma} \langle v_* \rangle^{2k} \right) \\
& + A_2 \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k} \langle v_* \rangle^{2(p-k)+\gamma} + \langle v \rangle^{2(p-k)} \langle v_* \rangle^{2k+\gamma} \right) \\
& + 2p(p-1) A_2 \varepsilon_p \sum_{k=0}^{k_p-1} \binom{p-2}{k} \left(\langle v \rangle^{2(k+1)+\gamma} \langle v_* \rangle^{2(p-1-k)} + \langle v \rangle^{2(p-1-k)+\gamma} \langle v_* \rangle^{2(k+1)} \right) \\
& + 2p(p-1) A_2 \varepsilon_p \sum_{k=0}^{k_p-1} \binom{p-2}{k} \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-1-k)+\gamma} + \langle v \rangle^{2(p-1-k)} \langle v_* \rangle^{2(k+1)+\gamma} \right).
\end{aligned}$$

(II) Under the assumption (H3) which is rewritten in the form

$$(3.13) \quad \gamma = 2, \quad 1 < p_1 < \infty, \quad A_{p_1}^* := |\mathbb{S}^{N-2}| \left(\int_0^\pi [b(\cos \theta)]^{p_1} \sin^{N-2} \theta \, d\theta \right)^{1/p_1} < \infty$$

we have for all $p \geq p_0 = (12A_{p_1}^*/A_0)^{2q_1}$

$$\begin{aligned}
(3.14) \quad & L_B [\Delta \langle \cdot \rangle^{2p}] (v, v_*) \\
& \leq \frac{12A_{p_1}^*}{p^\eta} \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-k)} + \langle v \rangle^{2(p-k+1)} \langle v_* \rangle^{2k} \right) \\
& + \frac{12A_{p_1}^*}{p^\eta} \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k} \langle v_* \rangle^{2(p-k+1)} + \langle v \rangle^{2(p-k)} \langle v_* \rangle^{2(k+1)} \right) \\
& + \frac{A_0}{2} \langle v \rangle^{2p} \langle v_* \rangle^2 + \frac{A_0}{2} \langle v_* \rangle^{2p} \langle v \rangle^2 - \frac{A_0}{4} \langle v \rangle^{2(p+1)} - \frac{A_0}{4} \langle v_* \rangle^{2(p+1)}
\end{aligned}$$

where $q_1 = p_1/(p_1 - 1)$ and $\eta = 1/2q_1$.

Proof. **Part (I)** Let us write

$$L_B [\Delta \langle \cdot \rangle^{2p}] (v, v_*) = |v - v_*|^\gamma |\mathbb{S}^{N-2}| \int_0^\pi b(\cos \theta) \sin^N \theta L_p(v, v_*, \theta) \, d\theta$$

with

$$L_p(v, v_*, \theta) := \frac{1}{\sin^2 \theta |\mathbb{S}^{N-2}|} \int_{\mathbb{S}^{N-2}(\mathbf{k})} (\langle v' \rangle^{2p} + \langle v_*' \rangle^{2p} - \langle v \rangle^{2p} - \langle v_* \rangle^{2p}) \, d\omega.$$

We first prove that

$$\begin{aligned}
(3.15) \quad L_p(v, v_*, \theta) &\leq -\frac{1}{2} \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) \\
&+ \frac{1}{2} \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k} \langle v_* \rangle^{2p-2k} + \langle v \rangle^{2p-2k} \langle v_* \rangle^{2k} \right) \\
&+ 2p(p-1) \int_0^1 t \left(1 - \frac{\sin^2 \theta}{2} t \right)^{p-2} dt \\
&\times \sum_{k=0}^{k_p-1} \binom{p-2}{k} \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-1-k)} + \langle v \rangle^{2(p-1-k)} \langle v_* \rangle^{2(k+1)} \right).
\end{aligned}$$

Let us denote the shorthand

$$E(\theta) = \langle v \rangle^2 \cos^2 \theta / 2 + \langle v_* \rangle^2 \sin^2 \theta / 2, \quad h = \sqrt{|v|^2 |v_*|^2 - \langle v, v_* \rangle^2}.$$

Then

$$\langle v' \rangle^2 = E(\theta) + h \sin \theta (\mathbf{j} \cdot \omega), \quad \langle v_*' \rangle^2 = E(\pi - \theta) - h \sin \theta (\mathbf{j} \cdot \omega).$$

By Taylor's formula we have

$$\begin{aligned}
\left(E(\theta) \pm h \sin \theta (\mathbf{j} \cdot \omega) \right)^p &= \left(E(\theta) \right)^p \pm q \left(E(\theta) \right)^{p-1} h \sin \theta (\mathbf{j} \cdot \omega) \\
&+ p(p-1) \int_0^1 (1-t) \left(E(\theta) \pm t h \sin \theta (\mathbf{j} \cdot \omega) \right)^{p-2} dt (h \sin \theta (\mathbf{j} \cdot \omega))^2.
\end{aligned}$$

Look at the last term: We have for all $\theta \in (0, \pi), t \in [0, 1]$

$$\begin{aligned}
E(\theta) + t h \sin \theta |\mathbf{j} \cdot \omega| &\leq E(\theta) + \left(E(\pi - \theta) \right) t \\
&= \langle v \rangle^2 + \langle v_* \rangle^2 - \left(E(\pi - \theta) \right) (1-t) \\
&\leq \left(\langle v \rangle^2 + \langle v_* \rangle^2 \right) \left(1 - \frac{1-t}{2} \sin^2 \theta \right)
\end{aligned}$$

where we used

$$E(\pi - \theta) \geq (\langle v \rangle^2 + \langle v_* \rangle^2) \min\{\cos^2 \theta / 2, \sin^2 \theta / 2\} \geq (\langle v \rangle^2 + \langle v_* \rangle^2) \frac{\sin^2 \theta}{2}.$$

Since

$$\int_{\mathbb{S}^{N-2}(\mathbf{n})} (\mathbf{j} \cdot \omega) d\omega = 0$$

it follows that

$$\begin{aligned}
(3.16) \quad L_p(v, v_*, \theta) &\leq \frac{1}{\sin^2 \theta} \left((E(\theta))^p + (E(\pi - \theta))^p - \langle v \rangle^{2p} - \langle v_* \rangle^{2p} \right) \\
&+ 2p(p-1) \left(\langle v \rangle^2 + \langle v_* \rangle^2 \right)^{p-2} h^2 \int_0^1 t \left(1 - \frac{\sin^2 \theta}{2} t \right)^{p-2} dt.
\end{aligned}$$

We next prove that for $p \geq 3$ and $k_p = \lfloor (p+1)/2 \rfloor$

$$(3.17) \quad \frac{1}{\sin^2 \theta} \left((E(\theta))^p + (E(\pi - \theta))^p - \langle v \rangle^{2p} - \langle v_* \rangle^{2p} \right) \\ \leq -\frac{1}{2} \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) + \frac{1}{2} \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k} \langle v_* \rangle^{2p-2k} + \langle v \rangle^{2p-2k} \langle v_* \rangle^{2k} \right).$$

In fact using Lemma 3.1 we have

$$\begin{aligned} & (E(\theta))^p + (E(\pi - \theta))^p \\ & \leq \sum_{k=0}^{k_p} \binom{p}{k} \left([\langle v \rangle^2 \cos^2(\theta/2)]^k [\langle v_* \rangle^2 \sin^2(\theta/2)]^{p-k} \right. \\ & \quad \left. + [\langle v \rangle^2 \cos^2(\theta/2)]^{p-k} [\langle v_* \rangle^2 \sin^2(\theta/2)]^k \right) \\ & + \sum_{k=0}^{k_p} \binom{p}{k} \left([\langle v \rangle^2 \sin^2(\theta/2)]^k [\langle v_* \rangle^2 \cos^2(\theta/2)]^{p-k} \right. \\ & \quad \left. + [\langle v \rangle^2 \sin^2(\theta/2)]^{p-k} [\langle v_* \rangle^2 \cos^2(\theta/2)]^k \right) \\ & \leq \frac{\sin^2 \theta}{2} \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k} \langle v_* \rangle^{2p-2k} + \langle v \rangle^{2p-2k} \langle v_* \rangle^{2k} \right) \\ & + \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) \left(\cos^{2p}(\theta/2) + \sin^{2p}(\theta/2) \right) \end{aligned}$$

where we used the fact that $p \geq 3 \implies p - k_p \geq 1$ so that

$$\cos^{2k}(\theta/2) \sin^{2p-2k}(\theta/2), \sin^{2k}(\theta/2) \cos^{2p-2k}(\theta/2) \leq \frac{1}{4} \sin^2 \theta$$

for all $1 \leq k \leq k_p$. Since $p \geq 3$ implies

$$\cos^{2p}(\theta/2) + \sin^{2p}(\theta/2) \leq \cos^4(\theta/2) + \sin^4(\theta/2) = 1 - \frac{1}{2} \sin^2(\theta)$$

this gives (3.17).

Note that $h^2 \leq \langle v \rangle^2 \langle v_* \rangle^2$. Then using Lemma 3.1 again and recalling $k_p - 1 = k_{p-2} = \lfloor (p-1)/2 \rfloor$ we have

$$\left(\langle v \rangle^2 + \langle v_* \rangle^2 \right)^{p-2} h^2 \leq \sum_{k=0}^{k_p-1} \binom{p-2}{k} \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-1-k)} + \langle v \rangle^{2(p-1-k)} \langle v_* \rangle^{2(k+1)} \right).$$

This together with (3.16)-(3.17) concludes the proof of (3.15).

Using (3.15) and the definitions of $L_B[\Delta\varphi]$, A_2 and ε_p we obtain

$$\begin{aligned} L_B [\Delta\langle\cdot\rangle^{2p}] (v, v_*) &\leq -\frac{A_2}{2} \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) |v - v_*|^\gamma \\ &+ \frac{A_2}{2} \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k} \langle v_* \rangle^{2p-2k} + \langle v \rangle^{2p-2k} \langle v_* \rangle^{2k} \right) |v - v_*|^\gamma \\ &+ p(p-1)A_2\varepsilon_p \sum_{k=0}^{k_p-1} \binom{p-2}{k} \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-1-k)} + \langle v \rangle^{2(p-1-k)} \langle v_* \rangle^{2(k+1)} \right) |v - v_*|^\gamma. \end{aligned}$$

Next by $0 < \gamma \leq 2$ we have

$$(3.18) \quad |v - v_*|^\gamma \geq \frac{1}{2} \langle v \rangle^\gamma - \langle v_* \rangle^\gamma, \quad |v - v_*|^\gamma \geq \frac{1}{2} \langle v_* \rangle^\gamma - \langle v \rangle^\gamma.$$

Thus

$$\begin{aligned} & \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) |v - v_*|^\gamma = \langle v \rangle^{2p} |v - v_*|^\gamma + \langle v_* \rangle^{2p} |v - v_*|^\gamma \\ & \geq \langle v \rangle^{2p} \left(\frac{1}{2} \langle v \rangle^\gamma - \langle v_* \rangle^\gamma \right) + \langle v_* \rangle^{2p} \left(\frac{1}{2} \langle v_* \rangle^\gamma - \langle v \rangle^\gamma \right) \\ & = \frac{1}{2} \langle v \rangle^{2p+\gamma} + \frac{1}{2} \langle v_* \rangle^{2p+\gamma} - \langle v \rangle^{2p} \langle v_* \rangle^\gamma - \langle v_* \rangle^{2p} \langle v \rangle^\gamma. \end{aligned}$$

Moreover using

$$(3.19) \quad |v - v_*|^\gamma \leq 2(\langle v \rangle^\gamma + \langle v_* \rangle^\gamma)$$

we have

$$\begin{aligned} & \left(\langle v \rangle^{2k} \langle v_* \rangle^{2(p-k)} + \langle v \rangle^{2(p-k)} \langle v_* \rangle^{2k} \right) |v - v_*|^\gamma \\ & \leq 2 \left(\langle v \rangle^{2k} \langle v_* \rangle^{2(p-k)} + \langle v \rangle^{2(p-k)} \langle v_* \rangle^{2k} \right) (\langle v \rangle^\gamma + \langle v_* \rangle^\gamma) \\ & = 2 \left(\langle v \rangle^{2k+\gamma} \langle v_* \rangle^{2(p-k)} + \langle v \rangle^{2(p-k)+\gamma} \langle v_* \rangle^{2k} \right) \\ & + 2 \left(\langle v \rangle^{2k} \langle v_* \rangle^{2(p-k)+\gamma} + \langle v \rangle^{2(p-k)} \langle v_* \rangle^{2k+\gamma} \right). \end{aligned}$$

And similarly

$$\begin{aligned} & \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-1-k)} + \langle v \rangle^{2(p-1-k)} \langle v_* \rangle^{2(k+1)} \right) |v - v_*|^\gamma \\ & \leq 2 \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-1-k)} + \langle v \rangle^{2(p-1-k)} \langle v_* \rangle^{2(k+1)} \right) (\langle v \rangle^\gamma + \langle v_* \rangle^\gamma) \\ & = 2 \left(\langle v \rangle^{2(k+1)+\gamma} \langle v_* \rangle^{2(p-1-k)} + \langle v \rangle^{2(p-1-k)+\gamma} \langle v_* \rangle^{2(k+1)} \right) \\ & + 2 \left(\langle v \rangle^{2(k+1)} \langle v_* \rangle^{2(p-1-k)+\gamma} + \langle v \rangle^{2(p-1-k)+\gamma} \langle v_* \rangle^{2(k+1)+\gamma} \right). \end{aligned}$$

These together with (3.18) yield the estimate (3.12).

Part (II). We have for any $p \geq 1$

$$\begin{aligned} |v - v_*|^{-2} L_B[\Delta \langle \cdot \rangle^{2p}](v, v_*) &= 2 \int_{\mathbb{S}^N} b(\cos \theta) \langle v' \rangle^{2p} d\sigma - A_0 \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) \\ &\leq 2A_{p_1}^* \left(\frac{1}{|\mathbb{S}^{N-2}|} \int_{\mathbb{S}^N} \langle v' \rangle^{2pq_1} d\sigma \right)^{1/q_1} - A_0 \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) \end{aligned}$$

where we used Hölder inequality. We still have to prove

$$(3.20) \quad \left(\frac{1}{|\mathbb{S}^{N-2}|} \int_{\mathbb{S}^N} \langle v' \rangle^{2pq_1} d\sigma \right)^{1/q_1} \leq \frac{3}{p^\eta} \left(\langle v \rangle^2 + \langle v_* \rangle^2 \right)^p, \quad \eta = \frac{1}{2q_1}.$$

Let $\lambda = pq_1 > 1$. Using the inequality

$$|v + v_*| |v - v_*| \leq \langle v \rangle^2 + \langle v_* \rangle^2$$

and $N \geq 2$ we compute using (2.1) and the monotone increase of the function

$$x \mapsto \left(\frac{1+x}{2} \right)^\lambda + \left(\frac{1-x}{2} \right)^\lambda \quad \text{on } x \in [0, 1]$$

that

$$\begin{aligned} &\frac{1}{|\mathbb{S}^{N-2}|} \int_{\mathbb{S}^N} \langle v' \rangle^{2\lambda} d\sigma \\ &= \left(\langle v \rangle^2 + \langle v_* \rangle^2 \right)^\lambda \int_0^\pi \sin^{N-2} \theta \left(\frac{1}{2} + \frac{|v + v_*| |v - v_*|}{2(\langle v \rangle^2 + \langle v_* \rangle^2)} \cos \theta \right)^\lambda d\theta \\ &\leq \left(\langle v \rangle^2 + \langle v_* \rangle^2 \right)^\lambda \int_0^\pi \left(\frac{1 + \cos \theta}{2} \right)^\lambda d\theta \leq \left(\langle v \rangle^2 + \langle v_* \rangle^2 \right)^\lambda \sqrt{\frac{2\pi}{\lambda}} \end{aligned}$$

where we used the well-known inequality

$$\int_0^{\pi/2} \sin^n \theta d\theta < \sqrt{\frac{\pi}{2n}}$$

with $n = 2[\lambda]$. This yields (3.20).

From this and using Lemma 3.1 we obtain that for all $p \geq 3$

$$\begin{aligned} |v - v_*|^{-2} L_B [\Delta \langle \cdot \rangle^{2p}](v, v_*) &\leq \frac{6A_{p_1}^*}{p^\eta} \left(\langle v \rangle^2 + \langle v_* \rangle^2 \right)^p - A_0 \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right) \\ &\leq \frac{6A_{p_1}^*}{p^\eta} \sum_{k=1}^{k_p} \binom{p}{k} \left(\langle v \rangle^{2k} \langle v_* \rangle^{2(p-k)} + \langle v \rangle^{2(p-k)} \langle v_* \rangle^{2k} \right) - \left(A_0 - \frac{6A_{p_1}^*}{p^\eta} \right) \left(\langle v \rangle^{2p} + \langle v_* \rangle^{2p} \right). \end{aligned}$$

By definition of p_0 we see that

$$p \geq p_0 := \left(\frac{12A_{p_1}^*}{A_0} \right)^{2q_1} \implies \frac{6A_{p_1}^*}{p^\eta} \leq \frac{A_0}{2}$$

and so

$$\begin{aligned}
 & L_B [\Delta \langle \cdot \rangle^{2p}] (v, v_*) \\
 & \leq \frac{6A_{p_1}^*}{p^\eta} \sum_{k=1}^{k_p} \binom{p}{k} (\langle v \rangle^{2k} \langle v_* \rangle^{2(p-k)} + \langle v \rangle^{2(p-k)} \langle v_* \rangle^{2k}) |v - v_*|^2 \\
 & \quad - \frac{A_0}{2} (\langle v \rangle^{2p} + \langle v_* \rangle^{2p}) |v - v_*|^2.
 \end{aligned}$$

Therefore as shown in the above using (3.18)-(3.19) with $\gamma = 2$ we obtain (3.14). \square

Lemma 3.7. (I) *Suppose that $B(z, \sigma) = |z|^\gamma b(\cos \theta)$ satisfies the assumption (H0). Let $p \geq 3$, $\mu \in \mathcal{B}_s^+(\mathbb{R}^N)$ with $\|\mu\|_0 > 0$ and $s \geq 2p + \gamma$. Then*

$$(3.21) \quad \langle Q(\mu, \mu), \langle \cdot \rangle^{2p} \rangle \leq 2^{2p+1} A_2 \|\mu\|_2 \|\mu\|_{2p} - \frac{1}{4} A_2 \|\mu\|_0 \|\mu\|_{2p+\gamma}.$$

Furthermore if $0 < \gamma < 2$, then

$$\begin{aligned}
 (3.22) \quad & \frac{\langle Q(\mu, \mu), \langle \cdot \rangle^{2p} \rangle}{\|\mu\|_0 \Gamma(q)} \\
 & \leq \left(C_a q^{2-a} + C_a q^{3-a} \varepsilon_p \right) A_2 \|\mu\|_0 \mathcal{Z}_p + \frac{1}{2} \|\mu\|_2 A_2 z_q - \frac{q}{16} A_2 \|\mu\|_0 (z_q)^{1+\frac{1}{q}}
 \end{aligned}$$

where $q = ap$, $a = 2/\gamma$,

$$(3.23) \quad z_q = \frac{\|\mu\|_{\gamma q}}{\|\mu\|_0 \Gamma(q)},$$

$$(3.24) \quad \mathcal{Z}_p = \max_{k \in \{1, 2, \dots, k_p\}} \{z_{ak+1} z_{a(p-k)}, z_{ak} z_{a(p-k)+1}\}.$$

(II) *If $\gamma = 2$, and $B(v - v_*, \sigma) = |z|^\gamma b(\cos \theta)$ satisfies (H3) which is rewritten as in (3.13), and let*

$$p \geq p_0 := (12A_{p_1}^*/A_0)^{2q_1} \quad \text{where } 1/p_1 + 1/q_1 = 1$$

then

$$\begin{aligned}
 (3.25) \quad & \frac{\langle Q(\mu, \mu), \langle \cdot \rangle^{2p} \rangle}{\|\mu\|_0 \Gamma(p)} \\
 & \leq 48A_{p_1}^* p^{1-\eta} (\log p) \|\mu\|_0 \tilde{\mathcal{Z}}_p + \left(12A_{p_1}^* p^{1-\eta} + A_0/4 \right) \|\mu\|_2 z_p - \frac{p}{16} A_0 \|\mu\|_0 (z_p)^{1+\frac{1}{p}}
 \end{aligned}$$

where $\eta = 1/2q_1$ and

$$(3.26) \quad \tilde{\mathcal{Z}}_p = \max_{k \in \{1, 2, \dots, k_p\}} z_{k+1} z_{p-k}.$$

Proof. Substituting μ for $\mu/\|\mu\|_0$, we can assume that $\|\mu\|_0 = 1$.

Part (I). By part (I) of Lemma 3.6 we have

$$\begin{aligned}
\langle Q(\mu, \mu), \langle \cdot \rangle^{2p} \rangle &= \frac{1}{2} \iint_{\mathbb{R}^N \times \mathbb{R}^N} L_B [\Delta \langle \cdot \rangle^{2p}] (v, v_*) d\mu(v) d\mu(v_*) \\
&\leq -\frac{A_2}{4} \|\mu\|_{2p+\gamma} + \frac{A_2}{2} \|\mu\|_{2p} \|\mu\|_\gamma \\
&+ A_2 \sum_{k=1}^{k_p} \binom{p}{k} (\|\mu\|_{2k+\gamma} \|\mu\|_{2(p-k)} + \|\mu\|_{2k} \|\mu\|_{2(p-k)+\gamma}) \\
&+ 2p(p-1) A_2 \varepsilon_p \sum_{k=0}^{k_p-1} \binom{p-2}{k} (\|\mu\|_{2(k+1)+\gamma} \|\mu\|_{2(p-1-k)} + \|\mu\|_{2(k+1)} \|\mu\|_{2(p-1-k)+\gamma}).
\end{aligned}$$

Using Hölder inequality we have (for $s > 2$)

$$(3.27) \quad \|\mu\|_r \leq \|\mu\|_2^{\frac{s-r}{s-2}} \|\mu\|_s^{\frac{r-2}{s-2}}, \quad 2 \leq r \leq s$$

from which we obtain for all $s_1, s_2 \geq 2$ satisfying $s_1 + s_2 \leq 2p + 2$ we have

$$\|\mu\|_{s_1} \|\mu\|_{s_2} \leq \|\mu\|_2^{\frac{2p-s_1+2p-s_2}{2p-2}} \|\mu\|_{2p}^{\frac{s_1+s_2-4}{2p-2}} \leq \|\mu\|_2 \|\mu\|_{2p}$$

where we used $\|\mu\|_2 \leq \|\mu\|_{2p}$. Thus

$$\begin{aligned}
\langle Q(\mu, \mu), \langle \cdot \rangle^{2p} \rangle &\leq -\frac{A_2}{4} \|\mu\|_{2p+\gamma} + \frac{A_2}{2} \|\mu\|_2 \|\mu\|_{2p} \\
&+ 2A_2 \left\{ \sum_{k=1}^{k_p} \binom{p}{k} + 2p(p-1) \sum_{k=0}^{k_p-1} \binom{p-2}{k} \right\} 2 \|\mu\|_2 \|\mu\|_{2p} \\
&\leq -\frac{A_2}{4} \|\mu\|_{2p+\gamma} + \frac{A_2}{2} \|\mu\|_2 \|\mu\|_{2p} + 2A_2 (2^p - 1 + 2p(p-1)2^{p-2}) 2 \|\mu\|_2 \|\mu\|_{2p} \\
&\leq -\frac{A_2}{4} \|\mu\|_{2p+\gamma} + 2^{2p+1} A_2 \|\mu\|_2 \|\mu\|_{2p}
\end{aligned}$$

which proves (3.21) for $\|\mu\|_0 = 1$, where we used the inequality (3.1) and

$$2^p + p(p-1)2^{p-1} \leq 2^{2p-1}, \quad \forall p \geq 3.$$

Now suppose that $0 < \gamma < 2$. This implies $a = 2/\gamma > 1$. Recall definitions of z_q and Z_p in (3.23)-(3.24) with $\|\mu\|_0 = 1$. We have for all $1 \leq k \leq k_p$

$$\begin{aligned}
&\|\mu\|_{2k+\gamma} \|\mu\|_{2(p-k)} + \|\mu\|_{2k} \|\mu\|_{2(p-k)+\gamma} \\
&= \|\mu\|_{\gamma(ak+1)} \|\mu\|_{\gamma a(p-k)} + \|\mu\|_{\gamma ak} \|\mu\|_{\gamma(a(p-k)+1)} \\
&= z_{ak+1} z_{a(p-k)} \Gamma(ak+1) \Gamma(a(p-k)) + z_{ak} z_{a(p-k)+1} \Gamma(ak) \Gamma(a(p-k)+1) \\
&\leq Z_p \Gamma(ap+1) (B(ak+1, a(p-k)) + B(ak, a(p-k)+1)) \\
&= Z_p \Gamma(ap+1) B(ak, a(p-k)),
\end{aligned}$$

and for all $0 \leq k \leq k_p - 1$

$$\begin{aligned}
 & \|\mu\|_{2(k+1)+\gamma} \|\mu\|_{2(p-1-k)} + \|\mu\|_{2(k+1)} \|\mu\|_{2(p-1-k)+\gamma} \\
 &= z_{a(k+1)+1} z_{a(p-k-1)} \Gamma(a(k+1)+1) \Gamma(a(p-1-k)) \\
 &+ z_{a(k+1)} z_{a(p-1-k)+1} \Gamma(a(k+1)) \Gamma(a(p-1-k)+1) \\
 &\leq Z_p \Gamma(ap+1) \mathbb{B}(a(k+1), a(p-1-k)).
 \end{aligned}$$

This together with $\Gamma(ap+1)/\Gamma(ap) = ap = q$ and Lemma 3.3 and Lemma 3.7 gives

$$\begin{aligned}
 & \frac{\langle Q(\mu, \mu), \langle \cdot \rangle^{2p} \rangle}{\Gamma(q)} \leq Z_p q A_2 \sum_{k=1}^{k_p} \binom{p}{k} \mathbb{B}(ak, a(p-k)) \\
 &+ Z_p 2qp(p-1) A_2 \varepsilon_p \sum_{k=0}^{k_p-1} \binom{p-2}{k} \mathbb{B}(a(k+1), a(p-1-k)) \\
 &+ \frac{A_2 \|\mu\|_2}{2} z_q - \frac{A_2}{4\Gamma(q)} \|\mu\|_{2p+\gamma} \\
 (3.28) \quad & \leq Z_p A_2 C_a q^{2-a} + Z_p A_2 C_a q^{3-a} \varepsilon_p + \frac{A_2 \|\mu\|_2}{2} z_q - \frac{A_2}{4\Gamma(q)} \|\mu\|_{2p+\gamma}.
 \end{aligned}$$

For the negative term, using Hölder inequality and $\|\mu\|_0 = 1$ we have

$$\|\mu\|_{2p+\gamma} \geq \|\mu\|_{2p}^{1+\frac{\gamma}{2p}} = \|\mu\|_{\gamma q}^{1+\frac{1}{q}}, \quad q = ap = \frac{2}{\gamma} p$$

and so

$$\frac{1}{\Gamma(q)} \|\mu\|_{2p+\gamma} \geq (\Gamma(q))^{\frac{1}{q}} \left(\frac{\|\mu\|_{\gamma q}}{\Gamma(q)} \right)^{1+\frac{1}{q}} = (\Gamma(q))^{\frac{1}{q}} (z_q)^{1+\frac{1}{q}} \geq \frac{q}{4} (z_q)^{1+\frac{1}{q}}$$

where we have used the inequality $(\Gamma(q))^{\frac{1}{q}} \geq q/4$. Thus (3.22) (with $\|\mu\|_0 = 1$) follows from (3.28).

Part (II). In this case we have $\gamma = 2$, i.e. $a = 1$ so that $q = p$. By part (II) of Lemma 3.6 we have, as shown above, that (the special term $\|\mu\|_{2k} \|\mu\|_{2(p-k+1)}$ for $k = 1$ in the

sum should be treated singly)

$$\begin{aligned}
\frac{\langle Q(\mu, \mu), \langle \cdot \rangle^{2p} \rangle}{\Gamma(p)} &= \frac{1}{2\Gamma(p)} \iint_{\mathbb{R}^N \times \mathbb{R}^N} L_B [\Delta \langle \cdot \rangle^{2p}] (v, v_*) d\mu(v) d\mu(v_*) \\
&\leq \frac{1}{\Gamma(p)} \cdot \frac{12A_{p_1}^*}{p^\eta} \sum_{k=1}^{k_p} \binom{p}{k} (\|\mu\|_{2(k+1)} \|\mu\|_{2(p-k)} + \|\mu\|_{2k} \|\mu\|_{2(p-k+1)}) \\
&\quad + \frac{1}{4\Gamma(p)} A_0 \|\mu\|_2 \|\mu\|_{2p} - \frac{1}{\Gamma(p)} \frac{A_0}{4} \|\mu\|_{2(p+1)} \\
&= \frac{1}{\Gamma(p)} \cdot \frac{12A_{p_1}^*}{p^\eta} \sum_{k=2}^{k_p} \binom{p}{k} (\|\mu\|_{2(k+1)} \|\mu\|_{2(p-k)} + \|\mu\|_{2k} \|\mu\|_{2(p-k+1)}) \\
&\quad + \frac{1}{\Gamma(p)} \cdot \frac{12A_{p_1}^*}{p^\eta} \binom{p}{1} \|\mu\|_4 \|\mu\|_{2(p-1)} + \frac{1}{\Gamma(p)} \cdot \frac{12A_{p_1}^*}{p^\eta} \binom{p}{1} \|\mu\|_2 \|\mu\|_{2p} \\
&\quad + \frac{1}{4\Gamma(p)} A_0 \|\mu\|_2 \|\mu\|_{2p} - \frac{1}{\Gamma(p)} \frac{A_0}{4} \|\mu\|_{2(p+1)} \\
&\leq \tilde{Z}_p \frac{12A_{p_1}^*}{p^\eta} \cdot p \sum_{k=2}^{k_p} \binom{p}{k} B(k, p-k) + \tilde{Z}_p \cdot \frac{12A_{p_1}^*}{p^\eta} p \binom{p}{1} B(2, p-1) \\
&\quad + \left(12A_{p_1}^* p^{1-\eta} + \frac{A_0}{4} \right) \|\mu\|_{2z_p} - \frac{A_0}{16} (z_p)^{1+\frac{1}{p}} \\
&\leq \tilde{Z}_p \frac{12A_{p_1}^*}{p^\eta} \cdot p \sum_{k=1}^{k_p} \binom{p}{k} B(k, p-k) + \left(12A_{p_1}^* p^{1-\eta} + \frac{A_0}{4} \right) \|\mu\|_{2z_p} - \frac{A_0}{16} (z_p)^{1+\frac{1}{p}} \\
&\leq 48A_{p_1}^* p^{1-\eta} (\log p) \tilde{Z}_p + \left(12A_{p_1}^* p^{1-\eta} + \frac{A_0}{4} \right) \|\mu\|_{2z_p} - \frac{A_0}{16} (z_p)^{1+\frac{1}{p}}
\end{aligned}$$

where in the last inequality we used Lemma 3.3. This proves (3.25) for $\|\mu\|_0 = 1$. \square

Lemma 3.8. *Given any $A > 0, B > 0, \varepsilon > 0$, we have:*

(I) *The function*

$$Y(t) = \left(\frac{A}{B(1 - e^{-\varepsilon At})} \right)^{1/\varepsilon}, \quad t > 0$$

is the unique positive C^1 -solution of the equation

$$\frac{d}{dt} Y(t) = AY(t) - BY(t)^{1+\varepsilon}, \quad t > 0; \quad Y(0+) = \infty.$$

(II) *Let $u(t)$ be a non-negative function in $(0, \infty)$ with the properties that u is absolutely continuous on every bounded closed subinterval of $(0, \infty)$ and satisfies*

$$\left(\frac{d}{dt} u(t) - Au(t) + Bu(t)^{1+\varepsilon} \right) 1_{\{u(t) > Y(t)\}} \leq 0 \quad \text{a.e. } t \in (0, \infty).$$

Then $u(t) \leq Y(t)$ for any $t > 0$.

Proof. Part (I) is obvious. To prove part (II) we use the assumption on u and notice that the function $x \mapsto Bx^{1+\varepsilon} - Ax$ is increasing in $((A/B)^{1/\varepsilon}, \infty)$ and $Y(t) > (A/B)^{1/\varepsilon}$. Then it follows from the assumption that

$$\begin{aligned} & \left(\frac{d}{dt}u(t) - \frac{d}{dt}Y(t) \right) 1_{\{u(t) > Y(t)\}} \\ & \leq \left(B(Y(t))^{1+\varepsilon} - AY(t) - B(u(t))^{1+\varepsilon} + Au(t) \right) 1_{\{u(t) > Y(t)\}} \leq 0 \end{aligned}$$

for almost every $t > 0$. Thus by the absolute continuity of u we have for any $t > t_* > 0$

$$\begin{aligned} & (u(t) - Y(t))^+ \\ & = (u(t_*) - Y(t_*))^+ + \int_{t_*}^t \left(\frac{d}{d\tau}u(\tau) - \frac{d}{d\tau}Y(\tau) \right) 1_{\{u(\tau) > Y(\tau)\}} d\tau \leq (u(t_*) - Y(t_*))^+. \end{aligned}$$

From this we see it is enough to prove that for any $t > 0$ there is $t_* \in (0, t)$ such that $u(t_*) \leq Y(t_*)$. Otherwise there were $t_0 > 0$ such that $u(t) > Y(t)$ for all $t \in (0, t_0)$. By assumption on u , this implies

$$\frac{d}{dt}u(t) \leq Au(t) - B(u(t))^{1+\varepsilon} \quad \text{a.e. } t \in (0, t_0).$$

On the other hand, from the lower bound $Y(t) > (A/B)^{1/\varepsilon}$ we see that the function $t \mapsto u^{-\varepsilon}(t)$ is absolutely continuous on every bounded closed subinterval of $(0, t_0]$. We then compute for a.e. $t \in (0, t_0)$

$$\frac{d}{dt}(u^{-\varepsilon}(t)) \geq -\varepsilon Au^{-\varepsilon}(t) + \varepsilon B$$

and hence for any $0 < \tau < t_0$ we have by the absolute continuity of $t \mapsto u^{-\varepsilon}(t)e^{\varepsilon At}$ on $[\tau, t_0]$ that

$$u^{-\varepsilon}(t)e^{\varepsilon At} \geq u^{-\varepsilon}(\tau)e^{\varepsilon A\tau} + \frac{B(e^{\varepsilon At} - e^{\varepsilon A\tau})}{A}, \quad \forall t \in [\tau, t_0].$$

Omitting the positive term $u^{-\varepsilon}(\tau)e^{\varepsilon A\tau}$ and letting $\tau \rightarrow 0+$ leads to

$$u^{-\varepsilon}(t)e^{\varepsilon At} \geq \frac{B(e^{\varepsilon At} - 1)}{A}, \quad \forall t \in (0, t_0]$$

i.e.

$$u(t) \leq \left(\frac{A}{B(1 - e^{-\varepsilon At})} \right)^{1/\varepsilon} = Y(t) \quad \forall t \in (0, t_0]$$

which contradicts the assertion “ $u(t) > Y(t)$ for all $t \in (0, t_0)$ ”. This prove the existence of $t_* \in (0, t)$ for all $t > 0$ and therefore concludes the proof of the lemma. \square

4. PROOF OF THEOREM 1.2

For notation convenience we denote

$$\int_{\mathbb{R}^N} \varphi dF_t = \int_{\mathbb{R}^N} \varphi(v) dF_t(v), \quad \text{etc.}$$

And note that if F_t is a measure weak solution of Eq. (1.1), then for any $\varphi \in C_b^2(\mathbb{R}^N)$ we have

$$(4.1) \quad \int_{\mathbb{R}^N} \varphi dF_t = \int_{\mathbb{R}^N} \varphi dF_{t_0} + \int_{t_0}^t \langle Q(F_\tau, F_\tau), \varphi \rangle d\tau \quad \forall t > t_0 > 0.$$

Our proofs of the parts (a) and (b) of Theorem 1.2 are contained in the following three steps.

Step 1. We first prove that if F_t is a measure weak solution of Eq. (1.1) associated with the initial datum F_0 satisfying $\|F_0\|_0 > 0$ and

$$(4.2) \quad \|F_t\|_2 \leq \|F_0\|_2 \quad \forall t > 0$$

$$(4.3) \quad \sup_{t_0 \leq t \leq T} \|F_t\|_s < \infty \quad \forall 0 < t_0 < T < \infty, \quad \forall s > 2$$

then F_t conserves mass, momentum and energy, and F_t satisfies the moment estimates (1.14) and (1.16). Moreover for any $s \geq 0$ and any $\varphi \in L_{-s}^\infty \cap C^2(\mathbb{R}^N)$,

$$(4.4) \quad t \mapsto \langle Q(F_t, F_t), \varphi \rangle \quad \text{is continuous on } (0, \infty)$$

and

$$(4.5) \quad \frac{d}{dt} \int_{\mathbb{R}^N} \varphi dF_t = \langle Q(F_t, F_t), \varphi \rangle \quad \forall t > 0.$$

And these integrals are absolutely convergent for any $t > 0$.

Since our test function space for defining measure weak solutions is only $C_b^2(\mathbb{R}^N)$, we need a truncation-mollification approximation. Let $\chi \in C_c^\infty(\mathbb{R}^N)$ satisfy $0 \leq \chi \leq 1$ on \mathbb{R}^N and $\chi(v) = 1$ for $|v| \leq 1$, $\chi(v) = 0$ for $|v| \geq 2$. Given any $s \geq 0$ and any $\varphi \in L_{-s}^\infty \cap C^2(\mathbb{R}^N)$, let $\varphi_n(v) := \varphi(v)\chi(v/n)$. It is easily seen that $\varphi_n \in C_c^2(\mathbb{R}^N) \subset C_b^2(\mathbb{R}^N)$ and their Hessian matrices satisfy

$$\sup_{n \geq 1} |H_{\varphi_n}(v)| \leq C_\varphi \langle v \rangle^s.$$

Thus by (1.10) we have for any $s_1 > s + 2 + \gamma$

$$\sup_{n \geq 1} \frac{|L_B[\Delta\varphi_n](v, v_*)|}{\langle v \rangle^{s_1} + \langle v_* \rangle^{s_1}} \leq C_\varphi A_2 \frac{(\langle v \rangle^s + \langle v_* \rangle^s)|v - v_*|^{2+\gamma}}{\langle v \rangle^{s_1} + \langle v_* \rangle^{s_1}} \rightarrow 0$$

as $|v|^2 + |v_*|^2 \rightarrow \infty$, and by part (II) of Proposition 2.1, we deduce

$$\lim_{n \rightarrow \infty} L_B[\Delta\varphi_n](v, v_*) = L_B[\Delta\varphi](v, v_*) \quad \forall (v, v_*) \in \mathbb{R}^N \times \mathbb{R}^N.$$

Thus by (4.1) and using the assumption (4.3) and the dominated convergence theorem we obtain

$$\lim_{n \rightarrow \infty} \int_{t_0}^t \langle Q(F_\tau, F_\tau), \varphi_n \rangle d\tau = \int_{t_0}^t \langle Q(F_\tau, F_\tau), \varphi \rangle d\tau \quad \forall t > t_0 > 0$$

and thus (4.1) holds for all $\varphi \in \bigcup_{s \geq 0} L_{-s}^\infty \cap C^2(\mathbb{R}^N)$. Since $\varphi(v) = 1, v, |v|^2$ belong to $L_{-2}^\infty \cap C^2(\mathbb{R}^N)$ with $\Delta\varphi \equiv 0$, it follows that F_t conserves the mass, momentum and energy in the **open** interval $(0, \infty)$. Of course we need to show that F_t conserves the

mass, momentum and energy on the **closed** interval $[0, \infty)$. Since $\varphi = 1 \in C_b^2(\mathbb{R}^N)$, this implies that every measure solution conserves the mass, i.e.

$$\|F_t\|_0 = \|F_0\|_0 \quad \forall t > 0.$$

Therefore the fact that F_t conserves the energy on $[0, \infty)$ is equivalent to $\|F_t\|_2 = \|F_0\|_2$ for all $t > 0$. Let $\chi(v)$ be given above. For any $1 < R < \infty$, let $\chi_R(v) = \chi(v/R)$, $\varphi_R(v) = \langle v \rangle^2 \chi_R(v)$. Then $\varphi_R \in C_c^2(\mathbb{R}^N) \subset C_b^2(\mathbb{R}^N)$ so that by definition of measure weak solution we have for any $t > 0$

$$\|F_t\|_2 = \int_{\mathbb{R}^N} \langle v \rangle^2 dF_t \geq \int_{\mathbb{R}^N} \varphi_R dF_t = \int_{\mathbb{R}^N} \varphi_R dF_0 + \int_0^t \langle Q(F_\tau, F_\tau), \varphi_R \rangle d\tau$$

and hence

$$0 \leq \|F_0\|_2 - \|F_t\|_2 \leq \int_{\mathbb{R}^N} \langle v \rangle^2 1_{\{|v| \geq R\}} dF_0 + \left| \int_0^t \langle Q(F_\tau, F_\tau), \varphi_R \rangle d\tau \right|.$$

Thus first letting $t \rightarrow 0+$ and then letting $R \rightarrow \infty$ gives

$$\lim_{t \rightarrow 0+} (\|F_0\|_2 - \|F_t\|_2) = 0.$$

So F_t conserves the energy. The proof of conservation of momentum on $[0, \infty)$ is easy by using compactly supported smooth approximation for every $\varphi_i(v) = v_i$, $i = 1, 2, \dots, N$.

Next let's prove (4.4) and (4.5). Given any $s \geq 0$ and $\varphi \in L_{-s}^\infty \cap C^2(\mathbb{R}^N)$. For any $0 < \delta < T < \infty$, by denoting

$$C_{\delta, T, s} = \left(\sup_{\delta \leq t \leq T} \|F_t\|_s \right)^2 < \infty$$

and using (1.10) we have

$$\left| \int_{\mathbb{R}^N} \varphi dF_{t_1} - \int_{\mathbb{R}^N} \varphi dF_{t_2} \right| \leq C_\varphi A_2 C_{\delta, T, s} |t_1 - t_2| \quad \forall t_1, t_2 \in [\delta, T].$$

So

$$(4.6) \quad t \mapsto \int_{\mathbb{R}^N} \varphi dF_t \text{ is continuous in } t \in (0, \infty).$$

In order to prove (4.4), we need only to show that for any fixed $t > 0$ and any sequence $\{t_n\} \subset [t/2, 3t/2]$ satisfying $t_n \rightarrow t$ ($n \rightarrow \infty$) we have

$$(4.7) \quad \lim_{n \rightarrow \infty} \langle Q(F_{t_n}, F_{t_n}), \varphi \rangle = \langle Q(F_t, F_t), \varphi \rangle.$$

This is an application of Proposition 2.2. In fact by Proposition 2.1 we know that $(v, v_*) \mapsto L_B[\Delta\varphi](v, v_*)$ is continuous on $\mathbb{R}^N \times \mathbb{R}^N$, and as shown above

$$\frac{|L_B[\Delta\varphi](v, v_*)|}{\langle v \rangle^{s_1} + \langle v_* \rangle^{s_1}} \leq C_\varphi A_2 \frac{(\langle v \rangle^s + \langle v_* \rangle^s) |v - v_*|^{2+\gamma}}{\langle v \rangle^{s_1} + \langle v_* \rangle^{s_1}} \rightarrow 0$$

for all $s_1 > s + 2 + \gamma$ as $|v|^2 + |v_*|^2 \rightarrow \infty$. Since

$$\sup_{t/2 \leq \tau \leq 3t/2} \|F_\tau\|_{s_1} < \infty,$$

it follows from Proposition 2.2 and the weak-star convergence $F_{t_n} \rightharpoonup F_t$ ($n \rightarrow \infty$) (see (4.6)) that (4.7) (and therefore (4.4)) hold true.

The differential equation (4.5) follows from the continuity property (4.4) and from the equation (4.1) which has been proven for all $\varphi \in L^\infty_s \cap C^2(\mathbb{R}^N)$.

Now for any $s \geq 6$, let $p = s/2$ and take $\varphi(v) = \langle v \rangle^s$, which belongs to $L^\infty_s \cap C^2(\mathbb{R}^N)$. Then by Lemma 3.7 and (4.5) we have for any $t > 0$

$$\frac{d}{dt} \|F_t\|_s = \langle Q(F_t, F_t), \langle \cdot \rangle^s \rangle \leq 2^{s+1} A_2 \|F_0\|_2 \|F_t\|_s - \frac{1}{4} A_2 \|F_0\|_0 \|F_t\|_{s+\gamma}.$$

By (3.27) we have

$$\|F_t\|_s \leq (\|F_0\|_2)^{\frac{\gamma}{s+\gamma-2}} (\|F_t\|_{s+\gamma})^{\frac{s-2}{s+\gamma-2}}$$

i.e.

$$\|F_t\|_{s+\gamma} \geq (\|F_0\|_2)^{-\frac{\gamma}{s-2}} (\|F_t\|_s)^{1+\frac{\gamma}{s-2}}.$$

It follows that

$$\frac{d}{dt} \|F_t\|_s \leq 2^{s+1} A_2 \|F_0\|_2 \|F_t\|_s - \frac{1}{4} A_2 \|F_0\|_0 (\|F_0\|_2)^{-\frac{\gamma}{s-2}} (\|F_t\|_s)^{1+\frac{\gamma}{s-2}} \quad \forall t > 0.$$

By Lemma 3.8 we thus obtain

$$\|F_t\|_s \leq \left(\frac{2^{s+1} A_2 \|F_0\|_2}{\frac{1}{4} A_2 \|F_0\|_0 (\|F_0\|_2)^{-\frac{\gamma}{s-2}} \left(1 - \exp(-\frac{\gamma}{s-2} 2^{s+1} A_2 \|F_0\|_2 t)\right)} \right)^{\frac{s-2}{\gamma}} \quad \forall t > 0.$$

Since $s \geq 6$ implies $2^s \geq 8(s-2)$, this gives

$$\frac{\gamma}{s-2} 2^{s+1} A_2 \|F_0\|_2 \geq 16 A_2 \|F_0\|_2 \gamma =: \alpha$$

and hence

$$\|F_t\|_s \leq \|F_0\|_2 \left(\frac{\|F_0\|_2}{\|F_0\|_0} \cdot \frac{2^{s+3}}{1 - e^{-\alpha t}} \right)^{\frac{s-2}{\gamma}}, \quad t > 0, \quad s \geq 6.$$

From this we have for any $2 \leq s < 6$

$$\begin{aligned} \|F_t\|_s &\leq (\|F_0\|_2)^{\frac{6-s}{4}} (\|F_t\|_6)^{\frac{s-2}{4}} \leq (\|F_0\|_2)^{\frac{6-s}{4}} (\|F_0\|_2)^{\frac{s-2}{4}} \left(\frac{\|F_0\|_2}{\|F_0\|_0} \cdot \frac{2^9}{1 - e^{-\alpha t}} \right)^{\frac{4}{\gamma} \times \frac{s-2}{4}} \\ &= \|F_0\|_2 \left(\frac{\|F_0\|_2}{\|F_0\|_0} \cdot \frac{2^9}{1 - e^{-\alpha t}} \right)^{\frac{s-2}{\gamma}}. \end{aligned}$$

Maximizing the two cases and using $\max\{2^{s+3}, 2^9\} \leq 2^{s+7}$ for $s \geq 2$ we obtain

$$(4.8) \quad \|F_t\|_s \leq \|F_0\|_2 \left(2^{s+7} \frac{\|F_0\|_2}{\|F_0\|_0} \cdot \frac{1}{1 - e^{-\alpha t}} \right)^{\frac{s-2}{\gamma}} \quad \forall t > 0, \quad \forall s \geq 2.$$

The estimate (1.14) now follows from (4.8) since by using the inequality

$$\frac{1}{1 - e^{-\alpha t}} \leq \left(1 + \frac{1}{\alpha}\right) \left(1 + \frac{1}{t}\right)$$

we have

$$\|F_t\|_s \leq \|F_0\|_2 \left\{ 2^{s+7} \frac{\|F_0\|_2}{\|F_0\|_0} \left(1 + \frac{1}{\alpha}\right) \right\}^{\frac{s-2}{\gamma}} \left(1 + \frac{1}{t}\right)^{\frac{s-2}{\gamma}} = \mathcal{K}_s(F_0) \left(1 + \frac{1}{t}\right)^{\frac{s-2}{\gamma}}.$$

Note that from (4.8) we also have

$$(4.9) \quad \|F_t\|_s \leq \frac{\|F_0\|_0}{2^{s+7}} \left(2^{s+7} \frac{\|F_0\|_2}{\|F_0\|_0} \times \frac{1}{(1 - e^{-\alpha t})} \right)^{\frac{s}{\gamma}} \quad \forall t > 0, \quad \forall s \geq 2$$

which will be used below.

Now we are going to prove the exponential moment production estimate (1.16). We consider two cases:

Case 1. $0 < \gamma < 2$. That implies that $a = 2/\gamma > 1$. By Lemma 3.7 we have for all $q \geq 3a$ and $t > 0$

$$\begin{aligned} \frac{d}{dt} z_q(t) &= \frac{\langle Q(F_t, F_t), \langle \cdot \rangle^{2p} \rangle}{\|F_0\|_0 \Gamma(q)} \\ &\leq (C_a q^{2-a} + C_a q^{3-a} \varepsilon_p) A_2 \|F_0\|_0 Z_p(t) + \frac{1}{2} A_2 \|F_0\|_2 z_q(t) - \frac{q}{16} A_2 \|F_0\|_0 (z_q(t))^{1+\frac{1}{q}}, \end{aligned}$$

where $p = q/a \geq 3$, and

$$z_q(t) = \frac{\|F_t\|_{\gamma q}}{\|F_0\|_0 \Gamma(q)}, \quad Z_p(t) = \max_{k \in \{1, 2, \dots, k_p\}} \{z_{ak+1}(t) z_{a(p-k)}(t), z_{ak}(t) z_{a(p-k)+1}(t)\}.$$

Using $0 < \gamma < 2$ and Lemma 3.4 we have

$$C_a q^{2-a} + C_a q^{3-a} \varepsilon_p = o(1)q \quad (q \rightarrow \infty)$$

so that there is a positive integer n_0 , depending only on $b(\cdot)$ and γ , such that

$$q_0 := (a-1)n_0 \geq 3a \quad \text{and} \quad C_a q^{2-a} + C_a q^{3-a} \varepsilon_p \leq \frac{q}{32} \quad \forall q \geq q_0.$$

Since

$$q \geq q_0 \geq 3a \implies \frac{A_2 \|F_0\|_2}{2} < 16 A_2 \|F_0\|_2 \gamma q = \alpha q,$$

it follows that

$$(4.10) \quad \frac{d}{dt} z_q(t) \leq \frac{A_2 \|F_0\|_0 q}{32} Z_p(t) + \alpha q z_q(t) - \frac{q}{16} A_2 \|F_0\|_0 (z_q(t))^{1+\frac{1}{q}} \quad \forall q \geq q_0.$$

Let

$$\Theta := 2^{\gamma q_0 + 7} \frac{\|F_0\|_2}{\|F_0\|_0}, \quad Y_q(t) = \left(\frac{\Theta}{1 - e^{-\alpha t}} \right)^q, \quad t > 0.$$

Then Y_q satisfies the equation

$$\frac{d}{dt} Y_q(t) = \alpha q Y_q(t) - \frac{\alpha q}{\Theta} (Y_q(t))^{1+\frac{1}{q}}, \quad t > 0; \quad Y_q(0+) = \infty.$$

We now prove that

$$(4.11) \quad z_q(t) \leq Y_q(t) \quad \forall t > 0, \quad \forall q \geq 1.$$

To do this, it suffices to show that

$$(4.12) \quad z_q(t) \leq Y_q(t) \quad \forall t > 0, \quad \forall q \in [1, n\delta], \quad n = n_0, n_0 + 1, \dots$$

where $\delta = a - 1 > 0$. First of all it is easily seen that (4.12) holds for $n = n_0$. In fact by definition of $z_q(t), Y_q(t)$, (4.9) and $\Gamma(q) = \Gamma(q + 1)/q \geq 1/2$, we have for all $1 \leq q \leq q_0 = n_0\delta$

$$z_q(t) \leq 2 \frac{\|F_t\|_{\gamma q}}{\|F_0\|_0} \leq \left(2^{\gamma q + 7} \frac{\|F_0\|_2}{\|F_0\|_0} \cdot \frac{1}{1 - e^{-\alpha t}} \right)^q \leq Y_q(t) \quad \forall t > 0.$$

Suppose that (4.12) holds for an integer $n \geq n_0$. Take any $q \in [n\delta, (n + 1)\delta]$. Then $q \geq n\delta \geq n_0\delta = q_0$ and so (4.10) holds for such q . Since for all integer $1 \leq k \leq k_p = [(p + 1/2)]$ there holds

$$1 < ak < ak + 1 \leq \frac{(n + 1)\delta + a}{2} + 1 < n\delta$$

$$1 < a(p - k) < a(p - k) + 1 \leq (n + 1)\delta - \delta = n\delta$$

it follows from the inductive hypothesis that

$$\begin{aligned} z_{ak+1}(t)z_{a(p-k)}(t) &\leq Y_{ak+1}(t)Y_{a(p-k)}(t) = (Y_q(t))^{1+\frac{1}{q}}, \\ z_{ak}(t)z_{a(p-k)+1}(t) &\leq Y_{ak}(t)Y_{a(p-k)+1}(t) = (Y_q(t))^{1+\frac{1}{q}}. \end{aligned}$$

Therefore by definition of $Z_p(t)$ we obtain

$$Z_p(t) \leq (Y_q(t))^{1+\frac{1}{q}}, \quad \forall t > 0, \quad \forall q \in [n\delta, (n + 1)\delta]$$

and hence by (4.10)

$$\frac{d}{dt}z_q(t) \leq \frac{A_2\|F_0\|_0}{32}q(Y_q(t))^{1+\frac{1}{q}} + \alpha pz_q(t) - \frac{A_2\|F_0\|_0}{16}q(z_q(t))^{1+\frac{1}{q}} \quad \forall t > 0$$

for all $q \in [n\delta, (n + 1)\delta]$. From this we obtain the following implication:

$$t > 0 \quad \text{and} \quad z_q(t) > Y_q(t) \quad \implies \quad \frac{d}{dt}z_q(t) \leq \alpha q z_q(t) - \frac{\alpha q}{\Theta} (z_q(t))^{1+\frac{1}{q}}$$

where we used the obvious fact that $\Theta = 2^{\gamma q_0 + 7} \frac{\|F_0\|_2}{\|F_0\|_0} > \alpha \cdot \frac{32}{A_2\|F_0\|_0}$. Thus by Lemma 3.8 we get $z_q(t) \leq Y_q(t)$ for all $t > 0$. This together with the inductive hypotheses implies that $z_q(t) \leq Y_q(t)$ for all $t > 0$ and all $q \in [1, (n + 1)\delta]$. This proves (4.12).

Now let

$$c(t) = \frac{1 - e^{-\alpha t}}{2\Theta}, \quad t > 0.$$

Then $[c(t)]^q z_q(t) \leq [c(t)]^q Y_q(t) = (1/2)^q$ so that by definition of $z_q(t)$ and (4.11) we get for all $t > 0$

$$\begin{aligned} (4.13) \quad \int_{\mathbb{R}^N} e^{c(t)\langle v \rangle^\gamma} dF_t(v) &= \|F_0\|_0 + \sum_{q=1}^{\infty} \frac{[c(t)]^q}{q!} \|F_t\|_{\gamma q} \\ &\leq \|F_0\|_0 + \|F_0\|_0 \sum_{q=1}^{\infty} [c(t)]^q z_q(t) \leq 2\|F_0\|_0. \end{aligned}$$

Case 2. $\gamma = 2$. From part (II) of Lemma 3.7 we have for all $p \geq p_0 := (12A_{p_1}^*/A_0)^{2q_1}$ (which is always larger than 5)

$$\begin{aligned} \frac{d}{dt}z_p(t) &\leq 48A_{p_1}^*p^{1-\eta}(\log p)\|F_0\|_0\tilde{Z}_p(t) \\ &\quad + (12A_{p_1}^*p^{1-\eta} + A_0/4)\|F_0\|_2z_p(t) - \frac{A_0\|F_0\|_0}{16}(z_p(t))^{1+\frac{1}{p}} \end{aligned}$$

where

$$\tilde{Z}_p(t) = \max_{k \in \{1, 2, \dots, k_p\}} z_{k+1}(t)z_{p-k}(t), \quad t > 0.$$

Let us fix an integer n_0 satisfying $n_0 \geq p_0$ such that

$$48A_{p_1}^*p^{1-\eta}\log p \leq \frac{A_2}{32}p, \quad \left(12A_{p_1}^*p^{1-\eta} + \frac{A_0}{4}\right) \leq 2A_2p \quad \forall p \geq n_0.$$

This gives

$$(4.14) \quad \frac{d}{dt}z_p(t) \leq \frac{A_2\|F_0\|_0}{32}p\tilde{Z}_p(t) + \alpha pz_p(t) - \frac{A_2\|F_0\|_0}{16}p(z_p(t))^{1+\frac{1}{p}} \quad \forall p \geq n_0.$$

It will be clear that in the present case all p can be chosen integers. Let

$$\Theta := 2^{2n_0+7}\frac{\|F_0\|_2}{\|F_0\|_0}, \quad Y_p(t) = \left(\frac{\Theta}{1 - e^{-\alpha t}}\right)^p, \quad t > 0; \quad p \geq 1.$$

Then Y_p satisfies the equation

$$\frac{d}{dt}Y_p(t) = \alpha p Y_p(t) - \frac{\alpha p}{\Theta}(Y_p(t))^{1+\frac{1}{p}}, \quad t > 0; \quad Y_p(0+) = \infty.$$

We now prove that

$$(4.15) \quad z_p(t) \leq Y_p(t) \quad \forall t > 0, \quad p = 1, 2, 3, \dots$$

As shown in the Case 1 one sees that (4.15) holds for all integer $1 \leq p \leq n_0$. Suppose that (4.15) holds true for some integer $q = p - 1$ with $p - 1 \geq n_0$. Let us check the case p . By $p - 1 \geq n_0 \geq 5$ we have $k_p + 1 \leq (p + 1)/2 + 1 \leq p - 1$ and so $z_{k+1}(t)z_{p-k}(t) \leq Y_{k+1}(t)Y_{p-k}(t) = (Y_p(t))^{1+\frac{1}{p}}$ hold for all $1 \leq k \leq k_p$. So

$$\tilde{Z}_p(t) = \max_{k \in \{1, 2, \dots, k_p\}} z_{k+1}(t)z_{p-k}(t) \leq (Y_p(t))^{1+\frac{1}{p}}.$$

Thus because of the differential inequality (4.14) we have

$$\frac{d}{dt}z_p(t) \leq \frac{A_2\|F_0\|_0}{32}p(Y_p(t))^{1+\frac{1}{p}} + \alpha pz_p(t) - \frac{A_2\|F_0\|_0}{16}p(z_p(t))^{1+\frac{1}{p}} \quad \forall t > 0$$

which proves the following implication:

$$t > 0 \quad \text{and} \quad z_p(t) > Y_p(t) \implies \frac{d}{dt}z_p(t) \leq \alpha pz_p(t) - \frac{\alpha p}{\Theta}(z_p(t))^{1+\frac{1}{p}}$$

where we used the fact that

$$\Theta = 2^{2n_0+7}\frac{\|F_0\|_2}{\|F_0\|_0} > \frac{32\alpha}{A_2\|F_0\|_0}.$$

Thus by using Lemma 3.8 we conclude that $z_p(t) \leq Y_p(t) \forall t > 0$. This proves (4.15).

As shown above (replacing γ with 2) by defining $c(t) = (1 - e^{-\alpha t})/2C_0$ we obtain

$$(4.16) \quad \int_{\mathbb{R}^N} e^{c(t)\langle v \rangle^2} dF_t(v) \leq 2\|F_0\|_0 \quad \forall t > 0.$$

This completes Step 1.

Step 2. Suppose that F_0 is absolutely continuous with respect to the Lebesgue measure, i.e. $dF_0(v) = f_0(v)dv$, and suppose that (moment bounds and finite entropy)

$$0 \leq f_0 \in \bigcap_{s \geq 0} L_s^1(\mathbb{R}^N) \quad \text{and} \quad 0 < \int_{\mathbb{R}^N} f_0(v) |\log f_0(v)| dv < \infty.$$

In this case we prove that there exists $\{f_t\}_{t \geq 0} \subset \bigcap_{s \geq 0} L_s^1(\mathbb{R}^N)$ such that the measure F_t defined by $dF_t = f_t dv$ is a conservative measure weak solution of Eq. (1.1) associated with the initial datum F_0 defined by $dF_0 = f_0 dv$, and F_t satisfies the moment production estimates (1.14) and (1.16).

To do this we consider some bounded truncations of the kernel B :

$$B_n(v - v_*, \sigma) = \min\{|v - v_*|^\gamma, n\} \min\{b(\cos \theta), n\}, \quad n = 1, 2, \dots$$

It is well-known that Eq. (1.1) with the bounded kernel B_n has a unique conservative solution $f_t^n(v)$ satisfying $f_0^n(v) = f_0(v)$ and $f^n \in C^1([0, \infty); L_s^1(\mathbb{R}^N)) \cap L_{\text{loc}}^\infty([0, \infty); L_s^1(\mathbb{R}^N))$ for all $s \geq 0$, and

$$(4.17) \quad \sup_{n \geq 1, t \geq 0} \int_{\mathbb{R}^N} f_t^n(v) (1 + |v|^2 + |\log f_t^n(v)|) dv < \infty.$$

Let $Q_{B_n}(\cdot, \cdot)$ (collision operator) and $A_{n,2}$ (angular momentum defined in (H0)) correspond to the kernel B_n , and define $dF_t^n = f_t^n dv$. Then $\|F_t^n\|_2 = \|F_0\|_2 = \|F_0\|_2$ and from the proof of Lemmas 3.6-3.7 we see that by omitting the negative term in the proofs of the two lemmas and notice that $A_{n,2} \leq A_2$ we have for all $p \geq 3$

$$\frac{d}{dt} \|F_t^n\|_{2p} = \langle Q_{B_n}(F_t^n, F_t^n), \langle \cdot \rangle^{2p} \rangle \leq 2^{2p+1} A_2 \|F_0\|_2 \|F_t^n\|_{2p}.$$

Thus for all $s \geq 6$, letting $p = s/2$ and recalling $\|f_t^n\|_{L_s^1} = \|F_t^n\|_s$ we obtain

$$(4.18) \quad \sup_{n \geq 1} \|f_t^n\|_{L_s^1} \leq \|f_0\|_{L_s^1} \exp(2^{s+1} A_2 \|F_0\|_2 t) \quad \forall t \geq 0.$$

From this and the basic estimate (1.10) we get for any $\varphi \in C_b^2(\mathbb{R}^N)$, any $T \in (0, \infty)$ and $t_1, t_2 \in [0, T]$

$$\left| \int_{\mathbb{R}^N} \varphi(v) f_{t_1}^n(v) dv - \int_{\mathbb{R}^N} \varphi(v) f_{t_2}^n(v) dv \right| \leq C_{\varphi, T} |t_1 - t_2|.$$

This together with (4.17) implies for any $\psi \in L^\infty(\mathbb{R}^N)$ and any $0 < T < \infty$

$$(4.19) \quad \sup_{t_1, t_2 \in [0, T], |t_1 - t_2| \leq \delta; n \geq 1} \left| \int_{\mathbb{R}^N} \psi f_{t_1}^n dv - \int_{\mathbb{R}^N} \psi f_{t_2}^n dv \right| \rightarrow 0 \quad \text{as } \delta \rightarrow 0+.$$

Since (4.17) implies that for every $t \geq 0$, $\{f_t^n\}_{n=1}^\infty$ is L^1 -weakly relatively compact, it follows from diagonal argument and (4.19) that there is a subsequence of $\{n\}$ (independent of t), still denoted as $\{n\}$, and a nonnegative measurable function $(t, v) \mapsto f_t(v)$ on $[0, \infty) \times \mathbb{R}^N$ satisfying $f_t \in L^1(\mathbb{R}^N)$ ($\forall t \geq 0$) such that for all $\psi \in L^\infty(\mathbb{R}^N)$

$$(4.20) \quad \lim_{n \rightarrow \infty} \int_{\mathbb{R}^N} \psi f_t^n dv = \int_{\mathbb{R}^N} \psi f_t dv \quad \forall t \geq 0.$$

And consequently

$$f_t \in \bigcap_{s \geq 0} L_s^1(\mathbb{R}^N) \quad (\forall t \geq 0),$$

and

$$(4.21) \quad \sup_{t \geq 0} \|f_t\|_{L_s^1} \leq \|f_0\|_{L_s^1}, \quad \sup_{0 \leq t \leq T} \|f_t\|_{L_s^1} < \infty \quad \forall 0 < T < \infty, \quad \forall s \geq 0,$$

and for any $s > 0$ and any $\psi \in L^\infty(\mathbb{R}^N)$

$$(4.22) \quad t \mapsto \int_{\mathbb{R}^N} \psi f_t dv \quad \text{is continuous on } [0, \infty).$$

Now we are going to show that f_t (or equivalently the measure F_t defined by $dF_t = f_t dv$) is a conservative weak solution of Eq. (1.1) with the kernel B . Given any $\varphi \in C_b^2(\mathbb{R}^N)$, we have by (1.10) and $B_n \leq B$

$$\sup_{n \geq 1} \frac{|L_{B_n} [\Delta\varphi](v, v_*)|}{\langle v \rangle^s + \langle v_* \rangle^s} \leq A_2 C_\varphi \frac{|v - v_*|^{2+\gamma}}{\langle v \rangle^s + \langle v_* \rangle^s} \rightarrow 0 \quad (|v|^2 + |v_*|^2 \rightarrow \infty)$$

for $s > 2 + \gamma$. Moreover by Proposition 2.1, $L_{B_n}[\Delta\varphi](v, v_*)$, $L_B[\Delta\varphi](v, v_*)$ are all continuous on $(v, v_*) \in \mathbb{R}^N \times \mathbb{R}^N$, and

$$\lim_{n \rightarrow \infty} \sup_{|v|+|v_*| \leq R} |L_{B_n} [\Delta\varphi](v, v_*) - L_B [\Delta\varphi](v, v_*)| = 0 \quad \forall 0 < R < \infty.$$

It follows from Proposition 2.2 that

$$\sup_{0 \leq t \leq T} \iint_{\mathbb{R}^N \times \mathbb{R}^N} |L_B [\Delta\varphi](v, v_*)| f_t(v) f_t(v_*) dv dv_* < \infty \quad \forall 0 < T < \infty,$$

$$\langle Q_{B_n}(f_t^n, f_t^n), \varphi \rangle \rightarrow \langle Q_B(f_t, f_t), \varphi \rangle \quad (n \rightarrow \infty) \quad \forall t \geq 0.$$

Again using Proposition 2.2 and (4.22) we conclude that

$$t \mapsto \langle Q_B(f_t, f_t), \varphi \rangle \quad \text{is continuous on } [0, \infty).$$

Finally using the dominated convergence theorem (in the t variable) we conclude that

$$\int_{\mathbb{R}^N} \varphi f_t dv = \int_{\mathbb{R}^N} \varphi f_0 dv + \int_0^t \langle Q_B(f_\tau, f_\tau), \varphi \rangle d\tau \quad \forall t \geq 0.$$

Thus f_t is a weak solution of Eq. (1.1). Let F_t be defined by $dF_t = f_t dv$. Therefore from $\|F_t\|_s = \|f_t\|_{L_s^1}$, (4.21), and Step 1 we conclude that F_t is a conservative measure weak solution of Eq. (1.1) associated with the initial datum F_0 and satisfies the moment production estimates (1.14) and (1.16).

Step 3. Let F_0 be the given measure in $\mathcal{B}_2^+(\mathbb{R}^N)$ with $\|F_0\|_0 > 0$. We shall prove the existence of a measure weak solution F_t that has all properties listed in the theorem.

First if $F_0 = c\delta_{v=v_0}$ ($c = \|F_0\|_0 > 0$) is a Dirac mass, then it is easily checked that the measure $F_t \equiv c\delta_{v=v_0}$ is a measure weak solution of Eq.(1.1) that conserves the mass, momentum and energy and satisfies the moment estimates.

Suppose F_0 is not a Dirac mass. We shall use **Mehler transform**: Let

$$(4.23) \quad \rho = \|F_0\|_0, \quad v_0 = \frac{1}{\rho} \int_{\mathbb{R}^N} v dF_0(v), \quad T = \frac{1}{N\rho} \int_{\mathbb{R}^N} |v - v_0|^2 dF_0(v).$$

Then $T > 0$ so that the Maxwellian used in the Mehler transform can be defined:

$$(4.24) \quad M(v) = \frac{e^{-|v|^2/2T}}{(2\pi T)^{N/2}}, \quad v \in \mathbb{R}^N.$$

The Mehler transform of F_0 is defined by

$$(4.25) \quad f_0^n(v) = e^{Nn} \int_{\mathbb{R}^N} M\left(e^n\left(v - v_0 - \sqrt{1 - e^{-2n}}(v_* - v_0)\right)\right) dF_0(v_*), \quad n \geq 1.$$

It is well-known that

$$(4.26) \quad \int_{\mathbb{R}^N} \begin{pmatrix} 1 \\ v \\ |v|^2 \end{pmatrix} f_0^n(v) dv = \int_{\mathbb{R}^N} \begin{pmatrix} 1 \\ v \\ |v|^2 \end{pmatrix} dF_0(v)$$

and for all $\psi \in L^{\infty}_2 C(\mathbb{R}^N)$

$$(4.27) \quad \lim_{n \rightarrow \infty} \int_{\mathbb{R}^N} \psi(v) f_0^n(v) dv = \int_{\mathbb{R}^N} \psi(v) dF_0(v).$$

For every n , choose $K_n > n$ such that

$$(4.28) \quad \int_{\mathbb{R}^N} \left(f_0^n(v) - \min\{f_0^n(v), K_n\} e^{-\frac{|v|^2}{K_n}} \right) \langle v \rangle^2 dv \leq \frac{\|F_0\|_0}{2n}.$$

Then let

$$\tilde{f}_0^n(v) = \min\{f_0^n(v), K_n\} e^{-|v|^2/n}, \quad dF_0^n(v) = \tilde{f}_0^n(v) dv.$$

We need to prove that

$$(4.29) \quad \lim_{n \rightarrow \infty} \int_{\mathbb{R}^N} \psi dF_0^n = \int_{\mathbb{R}^N} \psi dF_0 \quad \forall \psi \in L^{\infty}_2 C(\mathbb{R}^N).$$

Indeed we have

$$\left| \int_{\mathbb{R}^N} \psi dF_0^n - \int_{\mathbb{R}^N} \psi dF_0 \right| \leq \left| \int_{\mathbb{R}^N} \psi (\tilde{f}_0^n - f_0^n) dv \right| + \left| \int_{\mathbb{R}^N} \psi f_0^n dv - \int_{\mathbb{R}^N} \psi dF_0 \right|.$$

The second term converges to zero ($n \rightarrow \infty$). The first term also goes to zero: By (4.28) we have

$$\left| \int_{\mathbb{R}^N} \psi (\tilde{f}_0^n - f_0^n) dv \right| \leq C \int_{\mathbb{R}^N} \langle v \rangle^2 |\tilde{f}_0^n - f_0^n| dv \leq \frac{C}{2n}.$$

Since for every n , \tilde{f}_0^n satisfies the condition in the Step 2, there is a conservative measure weak solution F_t^n of Eq. (1.1) with the kernel B and the initial data F_0^n , such that F_t^n satisfies the moment estimate

$$\|F_t^n\|_s \leq \mathcal{K}_s(F_0^n)(1 + 1/t)^{\frac{s-2}{\gamma}} \quad \forall t > 0, \quad \forall s \geq 2.$$

Here recall that $\mathcal{K}_s(\cdot)$ is defined in (1.15). By the convergence (4.29) we have

$$\lim_{n \rightarrow \infty} \mathcal{K}_s(F_0^n) = \mathcal{K}_s(F_0) \quad \forall s \geq 2.$$

Thus for any $s \geq 2$, $C_s^* := \sup_{n \geq 1} \mathcal{K}_s(F_0^n) < \infty$ and hence

$$(4.30) \quad \sup_{n \geq 1} \|F_t^n\|_s \leq C_s^* \left(1 + \frac{1}{t}\right)^{\frac{s-2}{\gamma}} \quad \forall t > 0, \quad \forall s \geq 2.$$

Next we prove the equi-continuity of $\{F_t^n\}$ in $t \in [0, \infty)$ (in particular in the neighborhood of $t = 0$). It is only in this part that the logarithm $|\log(\sin \theta)|$ comes into play. Let

$$\lambda(\theta) := \frac{1}{1 + |\log(\sin \theta)|}, \quad 0 < \theta < \pi.$$

By (1.10) and $0 < \gamma\lambda(\theta) \leq \gamma \leq 2$ we have for any $\varphi \in C_b^2(\mathbb{R}^N)$

$$\left| \int_{\mathbb{S}^{N-2}(\mathbf{n})} \Delta\varphi \, d\omega \right| \leq C_\varphi \left| \int_{\mathbb{S}^{N-2}(\mathbf{n})} \Delta\varphi \, d\omega \right|^{\frac{2-\gamma\lambda(\theta)}{2}} \leq C_\varphi |v - v_*|^{2-\gamma\lambda(\theta)} (\sin \theta)^{2-\gamma\lambda(\theta)}$$

where here and below C_φ only depends on φ and N . Then by using

$$|v - v_*|^{\gamma+2-\gamma\lambda(\theta)} \leq 8 (\langle v \rangle^{\gamma+2-\gamma\lambda(\theta)} + \langle v_* \rangle^{\gamma+2-\gamma\lambda(\theta)})$$

and $(\sin \theta)^{-\gamma\lambda(\theta)} = e^{\gamma(1-\lambda(\theta))} \leq e^2$ and recalling (1.8) we obtain

$$|L_B[\Delta\varphi](v, v_*)| \leq C_\varphi \int_0^\pi b(\cos \theta) (\sin \theta)^N (\langle v \rangle^{\gamma+2-\gamma\lambda(\theta)} + \langle v_* \rangle^{\gamma+2-\gamma\lambda(\theta)}) \, d\theta.$$

So for all $t > 0$ (using Fubini's theorem and (4.30))

$$(4.31) \quad \begin{aligned} & \iint_{\mathbb{R}^N \times \mathbb{R}^N} |L_B[\Delta\varphi](v, v_*)| \, dF_t^n(v) \, dF_t^n(v_*) \\ & \leq C_\varphi \|F_0\|_0 \int_0^\pi b(\cos \theta) (\sin \theta)^N \|F_t^n\|_{\gamma+2-\gamma\lambda(\theta)} \, d\theta \\ & \leq C_{\varphi, F_0} \int_0^\pi b(\cos \theta) (\sin \theta)^N \left(1 + \frac{1}{t}\right)^{1-\lambda(\theta)} \, d\theta. \end{aligned}$$

Thus for all $t_1, t_2 \in [0, \infty)$ we compute (assuming $t_1 < t_2$)

$$(4.32) \quad \begin{aligned} & \int_{t_1}^{t_2} dt \iint_{\mathbb{R}^N \times \mathbb{R}^N} |L_B[\Delta\varphi](v, v_*)| \, dF_t^n(v) \, dF_t^n(v_*) \\ & \leq C_{\varphi, F_0} \int_0^\pi b(\cos \theta) (\sin \theta)^N \, d\theta (1 + t_2 - t_1)^{1-\lambda(\theta)} \int_0^{t_2-t_1} t^{\lambda(\theta)-1} \, dt \\ & = C_{\varphi, F_0} \int_0^\pi b(\cos \theta) (\sin \theta)^N (1 + |\log(\sin \theta)|) (1 + t_2 - t_1)^{1-\lambda(\theta)} (t_2 - t_1)^{\lambda(\theta)} \, d\theta \\ & =: C_{\varphi, F_0} \Omega(t_2 - t_1). \end{aligned}$$

Since

$$|\langle Q(F_t^n, F_t^n), \varphi \rangle| \leq \iint_{\mathbb{R}^N \times \mathbb{R}^N} |L_B[\Delta\varphi](v, v_*)| \, dF_t^n(v) \, dF_t^n(v_*),$$

it follows that

$$(4.33) \quad \begin{aligned} \sup_{n \geq 1} \left| \int_{\mathbb{R}^N} \varphi dF_{t_2}^n - \int_{\mathbb{R}^N} \varphi dF_{t_1}^n \right| &\leq \sup_{n \geq 1} \left| \int_{t_1}^{t_2} |\langle Q(F_t^n, F_t^n), \varphi \rangle| dt \right| \\ &\leq C_{\varphi, F_0} \Omega(|t_2 - t_1|) \rightarrow 0 \end{aligned}$$

as $|t_1 - t_2| \rightarrow 0$. We then deduce that for any $\psi \in C_c(\mathbb{R}^N)$ we have

$$(4.34) \quad \Lambda_\psi(\delta) := \sup_{|t_1 - t_2| \leq \delta; n \geq 1} \left| \int_{\mathbb{R}^N} \psi dF_{t_1}^n - \int_{\mathbb{R}^N} \psi dF_{t_2}^n \right| \rightarrow 0 \quad \text{as } \delta \rightarrow 0^+.$$

Since $C_c(\mathbb{R}^N)$ is separated, it follows from a diagonal argument that there is a subsequence of $\{n\}$ (independent of t), still denoted by $\{n\}$, and a family $\{F_t\}_{t \geq 0} \subset \mathcal{B}_2^+(\mathbb{R}^N)$, such that

$$(4.35) \quad \lim_{n \rightarrow \infty} \int_{\mathbb{R}^N} \psi dF_t^n = \int_{\mathbb{R}^N} \psi dF_t \quad \forall t \geq 0, \quad \forall \psi \in C_c(\mathbb{R}^N).$$

Using (4.30) and the fact that F_t^n are conservative solutions we have

$$(4.36) \quad \|F_t\|_2 \leq \|F_0\|_2, \quad \|F_t\|_s \leq C_s^* (1 + 1/t)^{\frac{s-2}{\gamma}} \quad \forall t > 0, \quad \forall s \geq 2.$$

Also by (4.35) and (4.34) we have

$$\left| \int_{\mathbb{R}^N} \psi dF_{t_1} - \int_{\mathbb{R}^N} \psi dF_{t_2} \right| \leq \Lambda_\psi(|t_1 - t_2|).$$

Hence

$$(4.37) \quad t \mapsto \int_{\mathbb{R}^N} \psi dF_t \quad \text{is continuous on } [0, \infty) \quad \forall \psi \in C_c(\mathbb{R}^N).$$

We now prove that F_t is a measure weak solution of Eq. (1.1). Given any $\varphi \in C_b^2(\mathbb{R}^N)$, by (4.36) we see that the derivation of (4.31) holds also for F_t and so

$$\iint_{\mathbb{R}^N \times \mathbb{R}^N} |L_B[\Delta\varphi](v, v_*)| dF_t(v) dF_t(v_*) < \infty \quad \forall t > 0.$$

Next by Proposition 2.1 the function $(v, v_*) \mapsto L_B[\Delta\varphi](v, v_*)$ is continuous on $\mathbb{R}^N \times \mathbb{R}^N$ and

$$(4.38) \quad \frac{|L_B[\Delta\varphi](v, v_*)|}{\langle v \rangle^s + \langle v_* \rangle^s} \leq C_\varphi A_2 \frac{|v - v_*|^{2+\gamma}}{\langle v \rangle^s + \langle v_* \rangle^s} \rightarrow 0 \quad (|v|^2 + |v_*|^2 \rightarrow \infty)$$

for all $s > 2 + \gamma$. Thus by using (4.30)-(4.35)-(4.38), Proposition 2.1 and Proposition 2.2 we have

$$(4.39) \quad \langle Q(F_t^n, F_t^n), \varphi \rangle \rightarrow \langle Q(F_t, F_t), \varphi \rangle \quad (n \rightarrow \infty) \quad \forall t > 0.$$

Similarly by using (4.36)-(4.37), Propositions 2.1 and 2.2 we conclude that

$$(4.40) \quad t \mapsto \langle Q(F_t, F_t), \varphi \rangle \quad \text{is continuous in } (0, \infty).$$

Note that the derivation of (4.32) also holds for F_t and hence we have for all $T \in (0, \infty)$

$$(4.41) \quad \int_0^T d\tau \iint_{\mathbb{R}^N \times \mathbb{R}^N} |L_B[\Delta\varphi](v, v_*)| dF_\tau(v) dF_\tau(v_*) \leq C_{\varphi, F_0} \Omega(T) < \infty.$$

Thus

$$t \mapsto \langle Q(F_t, F_t), \varphi \rangle \text{ belongs to } C((0, \infty)) \cap L^1_{\text{loc}}([0, \infty)).$$

And it also follows from (4.32)-(4.39) and the dominated convergence theorem that for all $t > 0$ we have

$$\int_0^t \langle Q(F_\tau^n, F_\tau^n), \varphi \rangle d\tau \rightarrow \int_0^t \langle Q(F_\tau, F_\tau), \varphi \rangle d\tau \quad (n \rightarrow \infty).$$

Thus in the integral equation of measures solutions F_t^n , letting $n \rightarrow \infty$ gives

$$\int_{\mathbb{R}^N} \varphi dF_t = \int_{\mathbb{R}^N} \varphi dF_0 + \int_0^t \langle Q(F_\tau, F_\tau), \varphi \rangle d\tau \quad \forall t > 0.$$

We have proved that F_t satisfies the conditions (i)-(ii) in the definition of measure weak solutions. So F_t is a measure weak solution of Eq. (1.1) associated with the initial datum F_0 . Finally from the moment estimates in (4.36) and Step 1 we conclude that the solution F_t conserves mass, momentum and energy, and satisfies the moment production estimates (1.14)-(1.16). This completes the proof of Theorem 1.2.

5. STABILITY ESTIMATES AND PROOF OF THEOREM 1.6

This section is devoted to the proof of Theorem 1.6. We begin with some basic facts about real Borel measures. As usual we denote

$$\mathcal{B}(\mathbb{R}^N) = \mathcal{B}_0(\mathbb{R}^N), \quad \|\mu\| = \|\mu\|_0 = |\mu|(\mathbb{R}^N).$$

For any $\mu \in \mathcal{B}(\mathbb{R}^N)$, let μ^+, μ^- be the positive and negative parts of μ , i.e. $\mu^\pm = \frac{1}{2}(|\mu| \pm \mu)$. Let $h : \mathbb{R}^N \rightarrow \mathbb{R}$ be the Borel function satisfying $|h(v)| \equiv 1$ such that $d\mu = hd|\mu|$. We may call h the sign function of μ . Then $d\mu^+ = \frac{1}{2}(1+h)d\mu$. So for any $\mu, \nu \in \mathcal{B}(\mathbb{R}^N)$, we have

$$(5.1) \quad |\mu - \nu| = \nu - \mu + 2(\mu - \nu)^+.$$

Lemma 5.1. *Let $\mu_t \in C([a, \infty); \mathcal{B}(\mathbb{R}^N))$, $\nu_a \in \mathcal{B}(\mathbb{R}^N)$, and*

$$\nu_t = \nu_a + \int_a^t \mu_s ds, \quad t \geq a,$$

and let $v \mapsto h_t(v)$ be the sign function of the measure ν_t and let $\kappa_t = (1+h_t)/2$ so that $d\nu_t^+ = \kappa_t d\nu_t$.

Then for any bounded Borel function ψ on \mathbb{R}^N , the functions

$$t \mapsto \int_{\mathbb{R}^N} \psi d\mu_t, \quad t \mapsto \int_{\mathbb{R}^N} \psi d|\mu_t| \quad \text{and} \quad t \mapsto \int_{\mathbb{R}^N} \psi d\mu_t^+$$

all belong to $L^1_{\text{loc}}([a, \infty))$ and for any $t \in [a, \infty)$ we have

$$(5.2) \quad \int_{\mathbb{R}^N} \psi d\nu_t = \int_{\mathbb{R}^N} \psi d\nu_a + \int_a^t ds \int_{\mathbb{R}^N} \psi d\mu_s,$$

$$(5.3) \quad \int_{\mathbb{R}^N} \psi d|\nu_t| = \int_{\mathbb{R}^N} \psi d|\nu_a| + \int_a^t ds \int_{\mathbb{R}^N} \psi h_s d\mu_s,$$

$$(5.4) \quad \int_{\mathbb{R}^N} \psi d\nu_t^+ = \int_{\mathbb{R}^N} \psi d\nu_a^+ + \int_a^t ds \int_{\mathbb{R}^N} \psi \kappa_s d\mu_s.$$

Proof. Since the half-sum of (5.2) and (5.3) is equal to (5.4), we only have to prove (5.2) and (5.3). The proof of (5.2) is easy and similar to that of (5.3). By simple function approximation, the proof of (5.3) can be reduced to the proof that for any Borel set $E \subset \mathbb{R}^N$, $t \mapsto \int_E h_t d\mu_t$ belongs to $L_{\text{loc}}^1([a, \infty))$ (and so does $t \mapsto \int_{\mathbb{R}^N} \psi h_t d\mu_t$ for any bounded Borel function ψ on \mathbb{R}^N) and

$$(5.5) \quad |\nu_t|(E) = |\nu_a|(E) + \int_a^t ds \int_E h_s d\mu_s, \quad t \in [a, \infty).$$

By assumption on μ_t , the strong derivative $\frac{d}{dt}\nu_t = \mu_t$ exists, and

$$\|\nu_{t_1} - \nu_{t_2}\| \leq \int_{t_1}^{t_2} \|\mu_s\| ds \quad \forall a \leq t_1 \leq t_2 < \infty.$$

This implies that for any Borel set $E \subset \mathbb{R}^N$, $t \mapsto |\nu_t|(E)$ is Lipschitz on every bounded interval of $[a, T]$: For all $a \leq t_1 \leq t_2 \leq T$

$$||\nu_{t_1}|(E) - |\nu_{t_2}|(E)| \leq |\nu_{t_1} - \nu_{t_2}|(E) \leq \int_{t_1}^{t_2} \|\mu_s\| ds \leq C_T |t_1 - t_2|$$

and so $t \mapsto |\nu_t|(E)$ is differentiable for almost every $t \in [a, \infty)$ and satisfies

$$|\nu_t|(E) = |\nu_a|(E) + \int_a^t \frac{d}{ds} |\nu_s|(E) ds \quad \forall t \in [a, \infty).$$

Therefore in order to prove (5.5) we only have to show that for all Borel set $E \subset \mathbb{R}^N$

$$(5.6) \quad \frac{d}{dt} |\nu_t|(E) = \int_E h_t d\mu_t, \quad \text{a.e. } t \in [a, \infty)$$

which also implies that $t \mapsto \int_E h_t d\mu_t$ belongs to $L_{\text{loc}}^1([a, \infty))$.

For any $t, s \in [a, \infty)$, using

$$|\nu_s|(E) = \int_E d|\nu_s| \geq \int_E h_t d\nu_s$$

we have

$$(5.7) \quad |\nu_s|(E) - |\nu_t|(E) \geq \int_E h_t d(\nu_s - \nu_t).$$

Now take any $t \in (a, \infty)$ such that the derivative $\frac{d}{dt} |\nu_t|(E)$ exists. By (5.7) we have

$$\begin{aligned} s > t &\implies \frac{|\nu_s|(E) - |\nu_t|(E)}{s - t} \geq \int_E h_t d\left(\frac{\nu_s - \nu_t}{s - t}\right), \\ s < t &\implies \frac{|\nu_s|(E) - |\nu_t|(E)}{s - t} \leq \int_E h_t d\left(\frac{\nu_s - \nu_t}{s - t}\right). \end{aligned}$$

Since $(\nu_s - \nu_t)/(s - t) \rightarrow \mu_t$ ($s \rightarrow t$) in norm $\|\cdot\|$, it follows that

$$\frac{d}{dt} |\nu_t|(E) = \lim_{s \rightarrow t} \frac{|\nu_s|(E) - |\nu_t|(E)}{s - t} = \int_E h_t d\mu_t.$$

This proves (5.6) and concludes the proof. \square

Lemma 5.2. *For any $\mu, \nu \in \mathcal{B}_s^+(\mathbb{R}^N)$ ($s \geq 0$) and any locally bounded Borel function $\psi \in L_{-s}^\infty(\mathbb{R}^N \times \mathbb{R}^N)$ we have*

$$(5.8) \quad \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v, v_*) d(\mu \otimes \mu - \nu \otimes \nu) = \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v_*, v) d(\mu \otimes \mu - \nu \otimes \nu),$$

$$(5.9) \quad \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v, v_*) d|\mu \otimes \mu - \nu \otimes \nu| = \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v_*, v) d|\mu \otimes \mu - \nu \otimes \nu|,$$

$$(5.10) \quad \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v, v_*) d(\mu \otimes \mu - \nu \otimes \nu)^+ = \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v_*, v) d(\mu \otimes \mu - \nu \otimes \nu)^+.$$

Proof. Equation (5.8) easily follows from Fubini's theorem. Equation (5.10) follows from (5.9) and the relation

$$d(\mu \otimes \mu - \nu \otimes \nu)^+ = \frac{1}{2} \left(d|\mu \otimes \mu - \nu \otimes \nu| + d(\mu \otimes \mu - \nu \otimes \nu) \right).$$

So we only have to prove (5.9). To do this we split ψ as $\psi = \psi^+ - (-\psi)^+$ so that we can assume that $\psi \geq 0$. Let $h(v, v_*)$ be the sign function of the measure $\mu \otimes \mu - \nu \otimes \nu$. Then applying (5.8) to $\psi(v, v_*)h(v, v_*)$ we have

$$\begin{aligned} & \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v, v_*) d|\mu \otimes \mu - \nu \otimes \nu| \\ &= \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v, v_*) h(v, v_*) d(\mu \otimes \mu - \nu \otimes \nu) \\ &= \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v_*, v) h(v_*, v) d(\mu \otimes \mu - \nu \otimes \nu) \\ &\leq \iint_{\mathbb{R}^N \times \mathbb{R}^N} \psi(v_*, v) d|\mu \otimes \mu - \nu \otimes \nu|. \end{aligned}$$

Replacing $\psi(v, v_*)$ with $\psi(v_*, v)$ we also obtain the reversed inequality. This proves (5.9). \square

Lemma 5.3. *Let $B(z, \sigma)$ be given by (1.3)-(1.4)-(1.5) with $b(\cdot)$ satisfying $A_0 < \infty$. Let $\mu \in \mathcal{B}_{2+\gamma}^+(\mathbb{R}^N)$, $\nu \in \mathcal{B}_{2\gamma}^+(\mathbb{R}^N)$, and let $h(v)$ be the sign function of $\mu - \nu$ and let $\kappa = \frac{1}{2}(1 + h)$ so that $\kappa d(\mu - \nu) = d(\mu - \nu)^+$. Then for any $\varphi \in C_b(\mathbb{R}^N)$ satisfying $0 \leq \varphi(v) \leq \langle v \rangle^2$ we have*

$$(5.11) \quad \begin{aligned} & \int_{\mathbb{R}^N} \varphi(v) \kappa(v) d(Q(\mu, \mu) - Q(\nu, \nu))(v) \\ & \leq E_\varphi + 2^{\gamma/2} A_0 \left(\|\mu\|_{2+\gamma} \|\mu - \nu\|_0 + \|\mu\|_2 \|\mu - \nu\|_\gamma \right) \end{aligned}$$

where

$$E_\varphi = A_0 2^\gamma \|\mu\|_\gamma \int_{\mathbb{R}^N} (\langle v \rangle^2 - \varphi(v)) \langle v \rangle^\gamma d\mu(v).$$

Proof. Since φ is bounded, there is no problem of integrability in the following derivation. For instance we can write

$$\int_{\mathbb{R}^N} \varphi(v) \kappa(v) d(Q(\mu, \mu) - Q(\nu, \nu))(v) = I^{(+)} - I^{(-)}$$

where

$$\begin{aligned} I^{(+)} &= \iint_{\mathbb{R}^N \times \mathbb{R}^N} L_B[\varphi \kappa](v, v_*) d(\mu \otimes \mu - \nu \otimes \nu), \\ I^{(-)} &= \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|) \varphi(v) \kappa(v) d(\mu \otimes \mu - \nu \otimes \nu). \end{aligned}$$

By definition of $B(z, \sigma)$ and $\varphi(v) \kappa(v) \leq \langle v \rangle^2$ we have

$$\begin{aligned} &L_B[\varphi \kappa](v, v_*) + L_B[\varphi \kappa](v_*, v) \\ &\leq \int_{\mathbb{S}^{N-1}} B(v - v_*, \sigma) (\langle v' \rangle^2 + \langle v'_* \rangle^2) d\sigma = A(|v - v_*|) (\langle v \rangle^2 + \langle v_* \rangle^2). \end{aligned}$$

Then using $d(\mu \otimes \mu - \nu \otimes \nu) \leq d(\mu \otimes \mu - \nu \otimes \nu)^+$ and Lemma 5.2 we compute

$$\begin{aligned} I^{(+)} &\leq \frac{1}{2} \iint_{\mathbb{R}^N \times \mathbb{R}^N} (L_B[\varphi \kappa](v, v_*) + L_B[\varphi \kappa](v_*, v)) d(\mu \otimes \mu - \nu \otimes \nu)^+ \\ &\leq \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|) \langle v \rangle^2 d(\mu \otimes \mu - \nu \otimes \nu)^+. \end{aligned}$$

Since $A(|v - v_*|) \leq A_0 2^\gamma \langle v \rangle^\gamma \langle v_* \rangle^\gamma$, $\langle v \rangle^2 - \varphi(v) \geq 0$, and $(\mu \otimes \mu - \nu \otimes \nu)^+ \leq \mu \otimes \mu$, it follows that

$$\begin{aligned} &\iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|) (\langle v \rangle^2 - \varphi(v)) d(\mu \otimes \mu - \nu \otimes \nu)^+ \\ &\leq A_0 2^\gamma \iint_{\mathbb{R}^N \times \mathbb{R}^N} \langle v \rangle^\gamma \langle v_* \rangle^\gamma (\langle v \rangle^2 - \varphi(v)) d(\mu \otimes \mu) \\ &= A_0 2^\gamma \|\mu\|_\gamma \int_{\mathbb{R}^N} \langle v \rangle^\gamma (\langle v \rangle^2 - \varphi(v)) d\mu(v) = E_\varphi. \end{aligned}$$

Therefore using

$$d(\mu \otimes \mu - \nu \otimes \nu)^+(v, v_*) \leq d\mu(v) d(\mu - \nu)^+(v_*) + d((\mu - \nu)^+(v)) d\nu(v_*)$$

we have

$$\begin{aligned} (5.12) \quad I^{(+)} &\leq E_\varphi + \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|) \varphi(v) d\mu(v) d(\mu - \nu)^+(v_*) \\ &\quad + \iint_{\mathbb{R}^N \times \mathbb{R}^N \times \mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|) \varphi(v) d(\mu - \nu)^+(v) d\nu(v_*). \end{aligned}$$

Similarly using $d(\mu \otimes \mu - \nu \otimes \nu)(v, v_*) = d\mu(v)d(\mu - \nu)(v_*) + d(\mu - \nu)(v)d\nu(v_*)$ and $\kappa(v)d(\mu - \nu)(v) = d(\mu - \nu)^+(v)$ we have

$$(5.13) \quad \begin{aligned} I^{(-)} &= \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|)\varphi(v)\kappa(v)d\mu(v)d(\mu - \nu)(v_*) \\ &\quad + \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|)\varphi(v)d(\mu - \nu)^+(v)d\nu(v_*). \end{aligned}$$

Canceling the common term in (5.12) and (5.13) and noticing that $d(\mu - \nu)^+(v_*) \leq d(\mu - \nu)(v_*) + d|\mu - \nu|(v_*)$ we obtain

$$(5.14) \quad \begin{aligned} &\int_{\mathbb{R}^N} \varphi(v)\kappa(v)d(Q(\mu, \mu) - Q(\nu, \nu)) \\ &\leq E_\varphi + \iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|)\varphi(v)d\mu(v)d|\mu - \nu|(v_*). \end{aligned}$$

Since $A(|v - v_*|)\varphi(v) \leq A_0 2^{\gamma/2}(\langle v \rangle^\gamma + \langle v_* \rangle^\gamma)\langle v \rangle^2$, it follows that

$$\iint_{\mathbb{R}^N \times \mathbb{R}^N} A(|v - v_*|)\varphi(v)d\mu(v)d|\mu - \nu|(v_*) \leq A_0 2^{\gamma/2}(\|\mu\|_{2+\gamma}\|\mu - \nu\|_0 + \|\mu\|_2\|\mu - \nu\|_\gamma)$$

which together with (5.14) proves (5.11). \square

Proof of Theorem 1.6.

Part (a). Recall that $B(z, \sigma) = b(\cos \theta)|z|^\gamma$ satisfies $A_0 < \infty$ and $0 < \gamma \leq 2$. Let F_t be a conservative measure weak solution of Eq. (1.1) with $F_t|_{t=0} = F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$. We prove that F_t is a measure strong solution.

First of all by $\|F_t\|_0, \|F_t\|_\gamma \leq \|F_0\|_2$ and Proposition 1.4 we have

$$\|Q^\pm(F_t, F_t)\|_0 \leq 4A_0\|F_0\|_2^2, \quad \forall t \geq 0,$$

$$\langle Q(F_t, F_t), \varphi \rangle = \int_{\mathbb{R}^N} \varphi dQ(F_t, F_t) \quad \forall \varphi \in C_b^2(\mathbb{R}^N), \quad \forall t \geq 0.$$

Since

$$t \mapsto \int_{\mathbb{R}^N} \varphi dQ(F_t, F_t) = \langle Q(F_t, F_t), \varphi \rangle \text{ belongs to } C((0, \infty)) \cap L_{\text{loc}}^1([0, \infty))$$

there is no problem of integrability and the integral equation for a measure weak solutions becomes

$$(5.15) \quad \int_{\mathbb{R}^N} \varphi dF_t = \int_{\mathbb{R}^N} \varphi dF_0 + \int_0^t ds \int_{\mathbb{R}^N} \varphi dQ(F_s, F_s).$$

Now take any $\varphi \in C_c^2(\mathbb{R}^N)$ satisfying $\|\varphi\|_{L^\infty} \leq 1$. We have

$$\left| \int_{\mathbb{R}^N} \varphi dQ(F_t, F_t) \right| \leq \|Q(F_t, F_t)\|_0 \leq 8A_0\|F_0\|_2^2, \quad \forall t \geq 0.$$

and thus using (5.15), for all $0 \leq t_1 < t_2 < \infty$

$$\left| \int_{\mathbb{R}^N} \varphi d(F_{t_2} - F_{t_1}) \right| \leq \int_{t_1}^{t_2} \left| \int_{\mathbb{R}^N} \varphi dQ(F_s, F_s) \right| ds \leq 8A_0\|F_0\|_2^2 |t_1 - t_2|.$$

Applying (1.21) this gives

$$(5.16) \quad \|F_{t_1} - F_{t_2}\|_0 \leq 8A_0 \|F_0\|^2 |t_1 - t_2|, \quad \forall t_1, t_2 \in [0, \infty)$$

which enable us to prove the strong continuity:

$$(5.17) \quad t \mapsto F_t \in C([0, \infty); \mathcal{B}_2(\mathbb{R}^N)), \quad t \mapsto Q^\pm(F_t, F_t) \in C([0, \infty); \mathcal{B}_0(\mathbb{R}^N)).$$

In fact applying the inequality (1.23) in Proposition 1.4 with $s = 0$ (recall that $0 < \gamma \leq 2$) we have

$$(5.18) \quad \|Q^\pm(F_t, F_t) - Q^\pm(F_{t_0}, F_{t_0})\|_0 \leq 8A_0 \|F_0\|_2 \|F_t - F_{t_0}\|_2, \quad t, t_0 \geq 0.$$

Fix $t_0 \in [0, \infty)$. Using (5.1), the conservation of mass and energy, $d(F_{t_0} - F_t)^+ \leq dF_{t_0}$, and (5.16) we have for any $R \geq 1$

$$\begin{aligned} \|F_t - F_{t_0}\|_2 &= 2 \int_{\mathbb{R}^N} \langle v \rangle^2 d(F_{t_0} - F_t)^+(v) \\ &\leq 2R^2 \int_{\langle v \rangle \leq R} d(F_{t_0} - F_t)^+(v) + 2 \int_{\langle v \rangle > R} \langle v \rangle^2 dF_{t_0}(v) \\ &\leq 2^4 A_0 R^2 |t - t_0| + 2 \int_{\langle v \rangle > R} \langle v \rangle^2 dF_{t_0}(v). \end{aligned}$$

Thus first letting $t \rightarrow t_0$ and then letting $R \rightarrow \infty$ leads to $\limsup_{t \rightarrow t_0} \|F_t - F_{t_0}\|_2 = 0$. This together with (5.18) proves (5.17).

From the strong continuity in (5.17) we have for all $\varphi \in C_b^2(\mathbb{R}^N)$

$$\int_0^t ds \int_{\mathbb{R}^N} \varphi dQ(F_s, F_s) = \int_{\mathbb{R}^N} \varphi d \left(\int_0^t Q(F_s, F_s) ds \right)$$

which together with (5.15) yields

$$\int_{\mathbb{R}^N} \varphi dF_t = \int_{\mathbb{R}^N} \varphi dF_0 + \int_{\mathbb{R}^N} \varphi d \left(\int_0^t Q(F_s, F_s) ds \right).$$

Therefore applying (1.21) we obtain

$$F_t = F_0 + \int_0^t Q(F_s, F_s) ds, \quad t \geq 0.$$

Since $t \mapsto Q^\pm(F_t, F_t) \in C([0, \infty); \mathcal{B}_0(\mathbb{R}^N))$, it follows that $t \mapsto F_t \in C^1([0, \infty); \mathcal{B}_0(\mathbb{R}^N))$ and

$$\frac{d}{dt} F_t = Q(F_t, F_t), \quad t \geq 0.$$

So F_t is a measure strong solution.

The converse is obvious: Every measure strong solution is a measure weak solution. (Recall our assumption that $\|F_t\|_2 < \infty$ for all times $t \geq 0$ for measure solutions, and $0 < \gamma \leq 2$.)

Parts (b)-(c)-(d). The proof of these three parts can be reduced to the proof of the following lemma:

Lemma 5.4. *Let us consider $F_0 \in \mathcal{B}_2^+(\mathbb{R}^N)$ with $\|F_0\|_0 > 0$. Let F_t be a conservative measure strong solutions of Eq. (1.1) with the initial datum*

$$F_t|_{t=0} = F_0 \in \mathcal{B}_2^+(\mathbb{R}^N),$$

which satisfies the moment production estimates in Theorem 1.2. Let G_t be any measure strong solutions of Eq. (1.1) on the time interval $[\tau, \infty)$ with initial data

$$G_t|_{t=\tau} = G_\tau \in \mathcal{B}_2^+(\mathbb{R}^N)$$

for some $\tau \geq 0$, and satisfying $\|G_t\|_2 \leq \|G_\tau\|_2$ for all $t \in [\tau, \infty)$.

Then the stability estimates (1.30) (for $\tau = 0$) and (1.31) (for $\tau > 0$) hold true.

Note that the existence of such a solution F_t as in the statement has been proven by Theorem 1.2 and part (a) of the present theorem. Therefore if Lemma 5.4 holds true, then by taking $G_0 = F_0$ (for the case $\tau = 0$) we get $G_t \equiv F_t$ on $[0, \infty)$ and hence this proves parts (b), (c) and (d).

Proof of Lemma 5.4. Our proof is divided into several steps. First of all for notation convenience we denote

$$H_t = F_t - G_t.$$

Step 1. Given any $r \in [\tau, \infty) \cap (0, \infty)$. We prove that

$$(5.19) \quad \|H_t\|_2 \leq \|G_\tau\|_2 - \|F_\tau\|_2 + 2\|(H_r)^+\|_2 + 4A_0 \left(\mathcal{K}_{2+\gamma}(F_0) \int_r^t (1 + 1/s) \|H_s\|_0 ds + \|F_0\|_2 \int_r^t \|H_s\|_\gamma ds \right), \quad t \geq r.$$

Here $\mathcal{K}_{2+\gamma}(F_0)$ is the constant in (1.15) with $s = 2 + \gamma$. To prove (5.19), we consider approximation: By $d|H_t| = dG_t - dF_t + 2d(H_t)^+$ we have

$$\|H_t\|_2 = \|G_t\|_2 - \|H_t\|_2 + 2 \lim_{n \rightarrow \infty} \int_{\mathbb{R}^N} \langle v \rangle_n^2 d(H_t)^+ \quad \text{with} \quad \langle v \rangle_n^2 = \min\{\langle v \rangle^2, n\}.$$

Let $v \mapsto h_t(v)$ be the sign function of H_t and $\kappa_t(v) = \frac{1}{2}(1 + h_t(v))$ so that $\kappa_t dH_t = d(H_t)^+$. Then applying Lemma 5.1 to the measure $H_t = H_r + \int_r^t (Q(F_s, F_s) - Q(G_s, G_s)) ds$ for $t \geq r$ and then using Lemma 5.3 we have

$$\begin{aligned} \int_{\mathbb{R}^N} \langle v \rangle_n^2 d(H_t)^+ &= \int_{\mathbb{R}^N} \langle v \rangle_n^2 d(H_r)^+ + \int_r^t ds \int_{\mathbb{R}^N} \langle v \rangle_n^2 \kappa_s(v) d(Q(F_s, F_s) - Q(G_s, G_s)) \\ &\leq \|(H_r)^+\|_2 + E_n(t) + 2A_0 \left(\int_r^t \|F_s\|_{2+\gamma} \|H_s\|_0 ds + \|F_0\|_2 \int_r^t \|H_s\|_\gamma ds \right), \quad t \in [r, \infty) \end{aligned}$$

where

$$E_n(t) = 4A_0 \int_r^t \|F_s\|_\gamma \left(\int_{\mathbb{R}^N} (\langle v \rangle^2 - \langle v \rangle_n^2) \langle v \rangle^\gamma dF_s \right) ds.$$

Since, by moment estimate (1.14),

$$\int_r^t \|F_s\|_\gamma \left(\int_{\mathbb{R}^N} \langle v \rangle^{2+\gamma} dF_s(v) \right) ds \leq \|F_0\|_2 \int_r^t \|F_s\|_{2+\gamma} ds < \infty, \quad t \in [r, \infty),$$

it follows from dominated convergence that $\lim_{n \rightarrow \infty} E_n(t) = 0$ and thus

$$\begin{aligned} \|H_t\|_2 &\leq \|G_t\|_2 - \|F_t\|_2 + 2\|(H_r)^+\|_2 \\ &+ 4A_0 \left(\int_r^t \|F_s\|_{2+\gamma} \|H_s\|_0 ds + \|F_0\|_2 \int_r^t \|H_s\|_\gamma ds \right), \quad \forall t \in [r, \infty). \end{aligned}$$

By assumption on F_t and G_t we have $\|G_t\|_2 - \|F_t\|_2 \leq \|G_\tau\|_2 - \|F_\tau\|_2$ and $\|F_s\|_{2+\gamma} \leq \mathcal{K}_{2+\gamma}(F_0)(1 + 1/s)$. This proves (5.19).

Step 2. Suppose $\tau > 0$. Then taking $r = \tau$ in (5.19) and using $\|G_\tau\|_2 - \|F_\tau\|_2 + 2\|(H_\tau)^+\|_2 = \|H_\tau\|_2$ we obtain

$$\|H_t\|_2 \leq \|H_\tau\|_2 + c_\tau \int_\tau^t \|H_s\|_2 ds \quad \forall t \in [\tau, \infty)$$

with $c_\tau = 4A_0(\mathcal{K}_{2+\gamma}(F_0) + \|F_0\|_2)(1 + \frac{1}{\tau})$. This gives (1.31) by Gronwall lemma.

The remaining steps deal with the case $\tau = 0$ and prove (1.30).

Step 3. If $\|H_0\|_2 \geq 1$, then using $\|F_t\|_2 = \|F_0\|_2$, $\|G_t\|_2 \leq \|G_0\|_2$ we have

$$\|H_t\|_2 \leq (1 + 2\|F_0\|_2)\|H_0\|_2 \quad \forall t \in [0, \infty).$$

So in the following we assume that $\|H_0\|_2 < 1$. Note that in this case we have

$$(5.20) \quad \|F_t \pm G_t\|_2 \leq 1 + 2\|F_0\|_2 =: C_0 \quad \forall t \geq 0.$$

Using Proposition 1.4 we have

$$\begin{aligned} \|H_t\|_0 &\leq \|H_0\|_0 + \int_0^t \|Q(F_s, F_s) - Q(G_s, G_s)\|_0 ds \\ &\leq \|H_0\|_0 + 4A_0 \int_0^t \left(\|F_s + G_s\|_\gamma \|H_s\|_0 + \|F_s + G_s\|_0 \|H_s\|_\gamma \right) ds \end{aligned}$$

and thus by $0 < \gamma \leq 2$ and (5.20) we obtain

$$(5.21) \quad \|H_t\|_0 \leq \|H_0\|_0 + 8A_0 C_0 \int_0^t \|H_s\|_2 ds, \quad \forall t \geq 0.$$

Step 4. Let $r > 0$ satisfy $\|H_0\|_2 \leq r \leq 1$. We prove that

$$(5.22) \quad U(r) := \sup_{0 \leq t \leq r} \|H_t\|_2 \leq 4(1 + 9A_0 C_0^2) \Psi_{F_0}(r).$$

First of all using (5.1) and $\|G_t\|_2 - \|F_t\|_2 \leq \|G_0\|_2 - \|F_0\|_2 \leq r$ we have

$$(5.23) \quad \|H_t\|_2 = \|G_t\|_2 - \|F_t\|_2 + 2\|(H_t)^+\|_2 \leq r + 2\|(H_t)^+\|_2$$

and for any $R \geq 1$

$$(5.24) \quad 2\|(H_t)^+\|_2 \leq 4R^2 \|H_t\|_0 + 2 \int_{|v|>R} \langle v \rangle^2 dF_t(v).$$

Next by (5.21), (5.20) and $\|H_0\|_2 \leq r$ we have

$$(5.25) \quad 4R^2 \|H_t\|_0 \leq 4(1 + 8A_0 C_0^2) R^2 r \quad \forall t \in [0, r].$$

Using the conservation of mass and energy we compute

$$\begin{aligned}
 \int_{|v|>R} \langle v \rangle^2 dF_t(v) &= \int_{\mathbb{R}^N} \langle v \rangle^2 dF_t(v) - \int_{|v|\leq R} \langle v \rangle^2 dF_t(v) \\
 &= \int_{\mathbb{R}^N} \langle v \rangle^2 dF_0(v) - \int_{|v|\leq R} \langle v \rangle^2 dF_0(v) - \int_0^t ds \int_{|v|\leq R} \langle v \rangle^2 dQ(F_s, F_s) \\
 &\leq \int_{|v|>R} \langle v \rangle^2 dF_0(v) + \int_0^t ds \int_{|v|\leq R} d\langle v \rangle^2 Q^-(F_s, F_s).
 \end{aligned}$$

For the last term we use $|v - v_*|^\gamma \leq \langle v \rangle^\gamma \langle v_* \rangle^\gamma \leq \langle v \rangle^2 \langle v_* \rangle^2$ to get for all $t \in [0, r]$

$$\int_0^t ds \int_{|v|\leq R} \langle v \rangle^2 dQ^-(F_s, F_s) \leq 2R^2 \int_0^t ds \int_{\mathbb{R}^N} dQ^-(F_s, F_s) \leq 2A_0 \|F_0\|_2^2 R^2 r.$$

Thus

$$(5.26) \quad \int_{|v|>R} \langle v \rangle^2 dF_t(v) \leq \int_{|v|>R} \langle v \rangle^2 dF_0(v) + 2A_0 \|F_0\|_2^2 R^2 r \quad \forall t \in [0, r].$$

Combining (5.24)-(5.25)-(5.26) gives

$$(5.27) \quad 2\|(H_t)^+\|_2 \leq 4(1 + 9A_0 C_0^2) R^2 r + 4 \int_{|v|>R} |v|^2 dF_0(v), \quad t \in [0, r].$$

Now choose $R = r^{-1/3}$. Then from (5.23), (5.27) we obtain

$$\|H_t\|_2 \leq r + 4(1 + 9A_0 C_0^2) r^{1/3} + 4 \int_{|v|>r^{-1/3}} |v|^2 dF_0(v), \quad t \in [0, r].$$

This gives (5.22) by definition of $\Psi_{F_0}(r)$ in (1.29).

Step 5. In the following we denote $C_i = \mathcal{R}_i(\gamma, A_0, A_2, \|F_0\|_0, \|F_0\|_2)$ for $(i = 1, 2, \dots, 6)$, where $\mathcal{R}_i(x_1, x_2, \dots, x_5)$ are some explicit positive continuous functions in $(\mathbb{R}_+)^{\otimes 5}$.

In (5.19) setting $\tau = 0, r = 1$ we have

$$\|H_t\|_2 \leq \|H_0\|_2 + 2\|H_1\|_2 + C_1 \int_1^t \|H_s\|_2 ds, \quad t \geq 1$$

so that Gronwall Lemma applies to get

$$(5.28) \quad \|H_t\|_2 \leq \left(\|H_0\|_2 + 2\|H_1\|_2 \right) \exp(C_1(t-1)), \quad t \geq 1.$$

Now we concentrate our estimate for $t \in [0, 1]$. In what follows we assume r satisfy

$$(5.29) \quad r > 0, \quad \|H_0\|_2 \leq r < 1.$$

Using (5.19) (with $\tau = 0$), $\|G_0\|_2 - \|F_0\|_2 \leq \|H_0\|_2 \leq r$, and $\|H_r\|_2 \leq U(r)$ we have

$$\|H_t\|_2 \leq r + 2U(r) + C_2 \left(\int_r^t \frac{1}{s} \|H_s\|_0 ds + \int_r^t \|H_s\|_\gamma ds \right), \quad t \in [r, 1].$$

Further, using (5.21) we compute for all $t \in [r, 1]$

$$\begin{aligned} \int_r^t \frac{1}{s} \|H_s\|_0 ds &\leq r \log(t/r) + 8A_0C_0 \int_r^t \frac{1}{s} \int_0^s \|H_\tau\|_2 d\tau ds \\ &\leq r |\log r| + 8A_0C_0 \int_0^t \|H_\tau\|_2 |\log \tau| d\tau. \end{aligned}$$

Thus for all $t \in [r, 1]$

$$(5.30) \quad \|H_t\|_2 \leq r + 2U(r) + C_2r |\log r| + C_3 \int_0^t \|H_s\|_2 (1 + |\log s|) ds.$$

Since $\|H_t\|_2 \leq U(r)$ for all $t \in [0, r]$, the inequality (5.30) holds for all $t \in [0, 1]$. Therefore by Gronwall Lemma we conclude

$$(5.31) \quad \|H_t\|_2 \leq C_4(r + U(r) + r |\log r|) \quad \forall t \in [0, 1].$$

In particular taking $t = 1$ yields the estimate for $\|H_1\|_2$ and thus from (5.28)-(5.29) we obtain

$$(5.32) \quad \|H_t\|_2 \leq C_5(r + U(r) + r |\log r|) \exp(C_1(t - 1)), \quad \forall t \in [1, \infty).$$

Combining (5.31)-(5.32) and the inequality $r |\log r| \leq r^{1/3}$ we conclude

$$(5.33) \quad \|H_t\|_2 \leq \Psi_{F_0}(r) \exp(C_6(1 + t)) \quad \forall t \geq 0.$$

Finally if $\|H_0\|_2 = 0$, then in (5.33) letting $r \rightarrow 0+$ leads to $\|H_t\|_2 \equiv 0$; if $\|H_0\|_2 > 0$, we take $r = \|H_0\|_2$. This proves (1.30) and completes the proof of the lemma. \square

Part (e). Let $dF_0 = f_0 dv$ with $0 \leq f_0 \in L_2^1(\mathbb{R}^N)$, and let F_t be the unique conservative measure strong solution of Eq. (1.1) with the initial datum F_0 . By the Lebesgue-Radon-Nikodym theorem, for every $t \geq 0$ we have a decomposition $dF_t = f_t dv + d\mu_t$ where $0 \leq f_t \in L_2^1(\mathbb{R}^N)$, $\mu_t \in \mathcal{B}_2^+(\mathbb{R}^N)$ and μ_t concentrates on a Lebesgue null set. We can assume that $\|f_0\|_{L^1} > 0$. Let

$$f_0^n(v) = \min\{f_0(v), n\} e^{-|v|^2/n}, \quad \text{and } dF_0^n(v) = f_0^n(v) dv.$$

By Step 2 of the proof of Theorem 1.2, for every n there is a conservative measure weak solution F_t^n with the initial datum F_0^n and $dF_t^n = f_t^n dv$, $0 \leq f_t^n \in L_2^1(\mathbb{R}^N)$ for all $t \geq 0$. By part (a), F_t^n is also a measure strong solution. Since $d(F_t - F_t^n) = (f_t - f_t^n) dv + d\mu_t$ we have $\|F_t - F_t^n\|_2 = \|f_t - f_t^n\|_{L_2^1} + \|\mu_t\|_2$. It is clear that

$$\|F_0 - F_0^n\|_2 = \|f_0 - f_0^n\|_{L_2^1} \rightarrow 0 \quad (n \rightarrow \infty)$$

since

$$\begin{aligned} \|F_0 - F_0^n\|_2 &= \|f_0 - f_0^n\|_{L_2^1} \\ &\leq \int_{f_0(v) > n} f_0(v) \langle v \rangle^2 dv + \int_{\mathbb{R}^N} f_0(v) (1 - e^{-|v|^2/n}) \langle v \rangle^2 dv \rightarrow 0 \quad (n \rightarrow \infty). \end{aligned}$$

Thus it follows from the stability estimate that for every fixed $t \geq 0$

$$\|f_t - f_t^n\|_{L_2^1} + \|\mu_t\|_2 = \|F_t - F_t^n\|_2 \leq e^{C(1+t)} \Psi_{F_0}(\|F_0 - F_0^n\|_2) \xrightarrow[n \rightarrow 0]{} 0$$

and therefore $\mu_t \equiv 0$. Thus $dF_t = f_t dv$ for all $t \geq 0$ where f_t is the unique conservative mild solution of Eq. (1.1) associated with the initial datum f_0 . This proves part (d).

Part (f). Suppose $F_0 \in \mathcal{B}^+(\mathbb{R}^N)$ is not a Dirac mass. We can assume that $\|F_0\|_0 > 0$. Let $f_0^n(v)$ be defined by (4.23)-(4.24) (the Mehler transform of F_0). By part (d), for every $n \geq 1$ there exists a unique conservative L^1 -solution f_t^n of Eq.(1.1) associated with the initial datum $f_t^n|_{t=0} = f_0^n$. If we define F_0^n, F_t^n by $dF_0^n = f_0^n(v)dv$, $dF_t^n = f_t^n(v)dv$, then by uniqueness and Theorem 1.2 we see that F_t^n satisfies the moment production estimates. Thus it is easily checked that the Step 3 (where there is no need of introducing \tilde{f}_0^n for the present case) within the proof of Theorem 1.2 is totally valid (and is in fact easier) for the present case. Therefore there is a subsequence of $\{f_t^n\}_{n=1}^\infty$, which we still denote as $\{f_t^n\}_{n=1}^\infty$, such that for the unique measure solution F_t of Eq. (1.1) with $F_t|_{t=0} = F_0$, the weak convergence (1.33) holds true. This completes the proof of Theorem 1.6. \square

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