The Lorentz covariant statistical physics and thermodynamics is formulated within the preferred frame approach. The transformation laws for geometrical and mechanical quantities such as volume and pressure as well as the Lorentz-invariant measure on the phase space are found using Lorentz transformations in absolute synchronization. Next, the probability density and partition function are investigated using the preferred frame approach, and the transformation laws for internal energy, entropy, temperature and other thermodynamical potentials are established. The Lorentz covariance of basic thermodynamical relations, including Clapeyron’s equation and Maxwell’s relations is shown. Finally, the relation of presented approach to the previous approaches to relativistic thermodynamics is briefly discussed.

Key words: preferred frame, covariant thermodynamics, transformation of temperature.

1. INTRODUCTION

The question of relativistic formulation of thermodynamics is almost as old as Special Relativity. The first attempt for the formulation of relativistic thermodynamics was done by Einstein, Planck and von Laue (7; 14) in 1907–1908. They concentrated on establishing of transformation laws of thermodynamical quantities by defining the transformation properties of work and heat. The main results of these works were the transformation laws for the change of entropy $dS$, temperature $T$ and heat transfer $\delta Q$

$$dS = dS_0, \quad T = T_0 \sqrt{1 - v^2}, \quad \delta Q = \delta Q_0 \sqrt{1 - v^2},$$

(1)

where the index 0 denotes values taken in the center of mass system of the gas, and $v$ is the velocity of the observer with respect to the center of mass system of the gas (hereafter we work in the natural system of units, where $c = 1$).

The derivation of transformation laws of thermodynamical quantities by Einstein and Planck was questioned in 60’s by Ott (16) and Arzelés (2). Their argumentation led to the transformation laws opposite to (1), namely

$$\delta Q = \frac{\delta Q_0}{\sqrt{1 - v^2}}, \quad T = \frac{T_0}{\sqrt{1 - v^2}},$$

(2)

1
Moreover, Landsberg (12; 13) had questioned the traditional relativistic generalization of the thermodynamics law and came into conclusion that temperature and heat transfer are invariant

\[ T = T_0, \quad \delta Q = \delta Q_0 \]  

(3)

(internal energy \( dU = dU_0 \) and pressure \( p = p_0 \) are invariant in Landsberg’s approach, too).

In this paper we look at this old-standing problem from a completely new point of view. Our approach is motivated by the fact that the proper formulation of quantum mechanics needs a preferred frame (3). In this way one avoids many serious interpretational problems in quantum mechanics (3, 14, 17, 18, 21). Moreover, Einstein himself had accepted the existence of such a “non-mechanical” preferred frame (8). We would like to point out that the notion of preferred frame has nothing to do with the obsolete notion of “ether”.

We will study consequences of the absolute synchronization scheme (3, 14, 21) and the existence of a preferred frame for thermodynamics and statistical physics. As a result we will find the transformation laws for thermodynamical quantities with as few as possible changes in the thermodynamical relations. It is remarkable that in the simplest physical situations the transformation law for the temperature is exactly the formula found by Einstein and Planck (1).

The paper is organized as follows. In the next section we sketch basic properties of the kinematics in absolute synchronization—namely we state the Lorentz transformations and show how geometrical and mechanical quantities transform in absolute synchronization. In Section 3 we construct the probability density and partition function in absolute synchronization approach, then we derive transformation properties for basic thermodynamical quantities, such as internal energy, entropy and temperature. Section 4 discusses some basic thermodynamical relations and shows their Lorentz covariance in absolute synchronization approach. The last section contains final remarks and conclusions.

2. KINEMATICS IN ABSOLUTE SYNCHRONIZATION

2.1. Lorentz transformations in absolute synchronization

In this section we briefly describe main results related to the absolute synchronization scheme. Derivation of these results can be found in (20, 21). The main idea is based on the well known fact that the definition of the time coordinate depends on the procedure used to synchronize clocks. The choice of this procedure is a convention (1, 8, 11, 13, 14, 22, 23) (this fact is known as “conventionality thesis”). Therefore, the form of Lorentz transformation depends on the synchronization scheme, and we can find a synchronization procedure which
leads to the desired form of Lorentz transformation. To perform such a choice under assumed absolute time synchronization we have to distinguish, at least formally, one inertial frame. Such a frame is called preferred frame \( \mathcal{O}_u \) [3, 20, 21]; it can be possibly identified with the cosmic background radiation frame. The four-velocity of the preferred frame with respect to the observer in an inertial frame \( \mathcal{O}_u \) is denoted by \( u^\mu \).

In absolute synchronization the transformation law of contravariant components of coordinates between inertial frames is expressed by the formula [4, 5, 21]

\[
x'(u')^\mu = [D(\Lambda, u)]^\mu_\nu [x(u)]^\nu,
\]

where \( \Lambda \) is an element of Lorentz group, \( u \) is a four-velocity and \( D(\Lambda, u) \) is \( 4 \times 4 \) matrix depending on \( \Lambda \) and \( u \). Transformation law for the contravariant components of four-velocity \( u^\mu \) is

\[
u'^\mu = [D(\Lambda, u)]^\mu_\nu u^\nu.
\]

Matrix \( D(\Lambda, u) \) for any rotation \( R \in \text{SO}(3) \) has the form

\[
D(R, u) = \begin{pmatrix} 1 & 0 \\ 0 & R \end{pmatrix},
\]

while for the boosts \( w \) is given by

\[
D(w, u) = \begin{pmatrix} \frac{1}{w^0} & 0 \\ -w & 1 + \frac{w \otimes w^T}{1 + (w^0)^2} - w^0 w \otimes u^T \end{pmatrix},
\]

where \( w^\mu \) is the four-velocity of the system \( \mathcal{O}_u' \) with respect to the system \( \mathcal{O}_u \) (here \( \otimes \) denotes the direct product of matrices). We can express the four-velocity \( w^\mu \) by the four-velocities of the preferred frame \( u \) and \( u' \) observed from the system \( \mathcal{O}_u \) and \( \mathcal{O}_u' \) respectively

\[
w^0 = \frac{u^0}{u'^0}, \quad w = \frac{(u^0 + u'^0)(u - u')}{1 + u^0 u'^0(1 + u \cdot u')},
\]

The components \( w^\mu \) can be expressed in terms of the velocity \( v = w/w^0 \) of the frame \( \mathcal{O}_w \) with respect to \( \mathcal{O}_u \) via the relation

\[
w^0 = \frac{1}{\sqrt{(1 + u^0 u \cdot v)^2 - (v)^2}}.
\]

Now the transformation law for the covariant components of coordinates reads

\[
(D^{-1}(w, u))^T = \begin{pmatrix} w^0 & w^T \\ 0 & I - \frac{w \otimes w^T}{1 + (w^0)^2} + \frac{w^0 w \otimes u^T}{1 + (w^0)^2} \end{pmatrix}.
\]

Comparing the transformation laws for the contravariant and covariant components of coordinates we see that under the transformation contravariant components of spatial coordinates mix with the time coordinate, while covariant do
not. Notice also that the time coordinate \( x^0 \) is rescaled by a positive factor only. Indeed, for Lorentz boosts we can rewrite (4) using (7) as follows

\[
x'^0 = \frac{1}{w^0} x^0, \quad x' = -w x^0 + M x,
\]

where

\[
M = I + \frac{w \otimes w^T}{1 + \sqrt{1 + (w)^2}} - u^0 w \otimes u^T; \quad (12)
\]

while (10) gives

\[
x'_0 = w^0 x_0 + w \cdot \underline{x}, \quad \underline{x}' = \underline{M} \underline{x}, \quad (13)
\]

where

\[
\underline{M} = I - \frac{w \otimes w^T}{1 + \sqrt{1 + (w)^2}} + \frac{u^0}{w^0} u \otimes u^T \quad (14)
\]

and \( \underline{x} \) denotes the covariant position three-vector. The above transformation laws apply to contravariant and covariant components of any tensor in the absolute synchronization. It is also important to stress that the time transformation law enables us to introduce the notion of absolute causality within this framework.

The line element

\[
ds^2 = g(u)_{\mu\nu} dx^\mu dx^\nu \quad (15)
\]

is invariant under Lorentz transformations if the metric tensor is of the following form

\[
[g(u)_{\mu\nu}] = \begin{pmatrix}
\frac{1}{u^0 u} & \frac{u^0 u^T}{u^0 u - I + (u)^2 u \otimes u^T}
\end{pmatrix}; \quad (16)
\]

while its contravariant counterpart is

\[
[g(u)^{\mu\nu}] = \begin{pmatrix}
\frac{(u^0)^2}{u^0 u} & u^0 u^T
\end{pmatrix}. \quad (17)
\]

From (17) it follows that the geometry of the three-space is Euclidean, i.e. \( dl^2 = d\underline{x}^2 \).

Note also that in every inertial frame \( u_\mu = (u_0, \underline{0}) \) (this follows immediately from \( u_\mu = g_{\mu\nu} u^\nu \), the relation \( u^\mu u_\mu = 1 \) and (17)), so the condition \( u^\mu u_\mu = 1 \) turns into the relation

\[
u^0 u_0 = 1. \quad (18)
\]

Finally, if the relationship of \( x^\mu \) with coordinates in the standard (Einstein–Poincaré) synchronization scheme is given by

\[
x^0_E = x^0 - u^0 \cdot x, \quad \underline{x}_E = \underline{x}, \quad (19)
\]

so the time lapses in the same point of the space are identical in both synchronizations. From (19) we are able to derive also the relationship between the velocities in absolute and standard synchronizations (21).
A more exhaustive discussion of the absolute synchronization, and its geometrical interpretation in terms of frame bundles is given in (5; 21).

2.2. Transformation properties of volume

The (three-) volume of the infinitesimal cube is defined by
\[ dV = dx^1 \wedge dx^2 \wedge dx^3 \equiv d^3 \mathbf{x} \]
where all the \( dx \)'s are taken in the same time, i.e. with \( dx^0 = 0 \). Note that the condition \( dx^0 = 0 \) is invariant under the transformations (4), because if \( dx^0 = 0 \) in the frame of the observer \( \mathcal{O}_u \), it follows from (11) that \( dx^0 = 0 \) for any other observer \( \mathcal{O}_{u'} \).

To find the transformation law for \( dV \) first consider the invariant quantity
\[ u \, d\sigma = u_\mu d\sigma^\mu = \frac{\epsilon^{0ijk}}{3!} u_0 dx_i \wedge dx_j \wedge dx_k \equiv u_0 d^3 \mathbf{x} \]
(20)
Using the metric tensor \( g^{\mu\nu}(u) \) we may rewrite \( dx_i \)'s in terms of \( dx^\mu \)'s and for \( dx^0 = 0 \) we obtain
\[ u_0 \, d\sigma^0 = u_0 \det (-I + (u^0)^2 u \otimes u^T) \, d^3 \mathbf{x} = -u_0 \, dV. \]
(21)
Therefore \( dV = -\frac{1}{u_0} u \, d\sigma \) transforms according to the Eq. (11) as follows
\[ dV' = w^0 \, dV, \]
(22)
so
\[ V' = w^0 V, \]
(23)
where \( V = \int_{t=\text{const}} dV \).

2.3. Invariant measure on the phase space

Now we construct an invariant measure on the phase space of a free particle.

Let us begin with an invariant measure in momentum space, assuming proper spectral conditions for the particle four-momentum, namely \( p^0 > 0 \) and \( p^2 = m^2 \) (see (5)):
\[ d\mu(p) = \theta(p^0) \delta(p^2 - m^2) \, d^4 p, \]
(24)
i.e.
\[ d\mu(p) = \frac{d^3 p}{2p^0}, \]
(25)
where \( p \) is covariant momentum three-vector. Multiplying (25) by the invariant \( 2(u_\mu p^\mu) \) we obtain an invariant measure on the phase space with proper scaling behavior:
\[ 2up \, d\mu(p) = u_0 d^3 \mathbf{p}. \]
(26)

Finally, taking into account (21), we obtain the following invariant measure on a single particle phase space
\[ d\Gamma = 2d\mu(p) \, u_\mu d\sigma^\mu \, u_\nu p^\nu = -d^3 \mathbf{x} \, d^3 \mathbf{p}. \]
(27)
We see that \( d\Gamma \) has the form analogous to the non-relativistic case.

### 2.4. Pressure

The pressure \( P \) of perfect fluid can be defined by the relation to its stress-energy tensor, namely by

\[
\sigma^{\mu\nu} = (\rho + P) \mathbf{w}^\mu \mathbf{w}^\nu - Pg^{\mu\nu},
\]

where \( \rho \) is the fluid density and \( \mathbf{w}^\mu \) is the four-velocity of fluid with respect to the observer \( O_u \). Pressure is then invariant

\[
P' = P
\]

and can be separated from the density using invariant relations

\[
\text{Tr} \sigma \equiv \sigma^{\mu\nu} g_{\mu\nu} = \rho + 3P, \quad \text{Tr} \sigma^2 = \rho^2 + 3P^2.
\]

Summarizing this section, we conclude that in the absolute synchronization scheme the volume and pressure have simple transformation laws \((23)\) and \((24)\), while the invariant measure on phase space has the very suggestive form \((27)\).

### 3. Statistical Mechanics and Absolute Synchronization

#### 3.1. Probability density and partition function

Consider the perfect gas of \( N \) non-interacting particles. We start with the following formula for a probability density of finding the \( i \)-th particle in an infinitesimal element of phase space \( d\Gamma_i \)

\[
\frac{1}{Z_i} \exp \left( -\beta (u^0)^n p^0_{(i)} \right),
\]

which is the natural modification of the Boltzmann–Maxwell distribution. Here \( \beta = \frac{1}{kT} \), \( n \) is an arbitrary power to be fixed later, \( Z_i \) is the normalization factor—partition function

\[
Z_i(\beta, V) = \int d\Gamma_i \exp \left( -\beta (u^0)^n p^0_{(i)} \right).
\]

The factor \( (u^0)^n \) is introduced to preserve the invariance of the argument of the exponential function under transformations \((3)\).

Therefore the probability distribution of finding \( N \) non-interacting identical particles of the gas in an element of the phase space \( d\Gamma_1 \cdots d\Gamma_N \) is

\[
\frac{1}{Z} \exp \left( -\beta (u^0)^n \sum_{i=1}^{N} p^0_{(i)} \right),
\]

\( Z \) is the normalization factor—partition function.
where the partition function $Z(\beta, V)$ for the gas is

$$Z(\beta, V) = \int \cdots \int d\Gamma_1 \cdots d\Gamma_N \exp \left( -\beta (u^0)^n \sum_{i=1}^N p_0^i \right)$$

$$= \left( V \int d^3 p \exp \left( -\beta (u^0)^n p^0 \right) \right)^N. \tag{34}$$

Of course the partition function must be an invariant of the Lorentz transformations (14)

$$Z' = Z. \tag{35}$$

This requires that the argument of the exponential in (34) also must be an invariant. Since $p^0 = \frac{1}{w^0} p^0$ and $u^0 = \frac{1}{w^0} u^0$ it follows that $\beta' = (w^0)^n + 1 \beta$, i.e.

$$T' = \frac{1}{(w^0)^n + 1} T. \tag{36}$$

### 3.2. Internal energy

In Lorentz covariant dynamics with absolute synchronization Hamiltonian, as the generator of the time translations, is identified with 0-th covariant component of four-momentum: $H_i \equiv p_0(i)$. Therefore energy of the system of $N$ non-interacting particles is equal to

$$H = \sum_{i=1}^N p_0(i). \tag{37}$$

The internal energy is defined as the mean value of Hamiltonian, i.e.,

$$U = \langle H \rangle = \frac{1}{Z} \int \cdots \int d\Gamma_1 \cdots d\Gamma_N \left( \sum_{k=1}^N p_0(k) \right) \exp \left( -\beta (u^0)^n \sum_{i=1}^N p_0^i \right)$$

$$= \frac{1}{Z} \left( V \int d^3 p p_0 \exp \left( -\beta (u^0)^n p^0 \right) \right)^N, \tag{38}$$

where $p_0$ and $p^0$ are covariant and contravariant components of the momentum of a single particle of the gas under consideration, respectively.

On the other hand in statistical physics internal energy is related to the partition function by

$$U = -\frac{\partial \ln Z}{\partial \beta} = -\frac{1}{Z} \frac{\partial Z}{\partial \beta}. \tag{39}$$

Taking into account Eq. (34) we obtain from (38) that

$$U = \frac{1}{Z} \left( (u^0)^n + 2 V \int d^3 p p_0 \exp \left( -\beta (u^0)^n p^0 \right) \right)^N. \tag{40}$$
Comparison of (38) and (40) fixes the power of $u^0$, so we have to choose $n = -2$. Therefore $\beta' = \beta/u^0$ and in consequence

$$U' = u^0U$$

and

$$T' = u^0T.$$  \hfill (42)

Therefore the probability distribution (33) finally takes the form

$$\frac{1}{Z} \exp \left( -u_0\beta \sum_{i=1}^{N} u^0 p(i) \right),$$

while the partition function is

$$Z(\beta, V) = \left( V \int d^3 p e^{-u_0\beta u^0 p} \right)^N,$$

where we have used (38) and $u^0 p = u_0 p^0$.

Notice, that in the preferred frame ($u^0 = 1, u = 0$) $Z$ takes the standard form.

3.3. Entropy

In fixed external conditions every simple thermodynamical system is uniquely described by its internal energy $U$ and volume $V$. The entropy $S = S(U, V)$ is a unique function of these parameters and is maximal for equilibrium states of the system.

We treat entropy as the measure of the information on the system. According to this approach we use Boltzmann definition of entropy

$$S(U, V) = -\sum_{i=1}^{N} \rho_i \ln \rho_i,$$

where $\rho_i$ are probabilities of finding the $i$-th particle in a given microscopic event realizing the macroscopic state of the system described by energy $U$ and volume $V$.

If the observer staying in the frame $O_u$ describes the system under consideration by $U, V$, the other observer, staying in the frame $O_{u'}$ describes the system by $U', V'$. Entropy $S'$ in the frame $O_{u'}$ is equal to

$$S'(U', V') = -\sum_{i=1}^{N} \rho_i \ln \rho_i,$$

because the macroscopic state $(U', V')$ is realized by the same microscopic events. So, entropy is invariant

$$S' = S.$$

(47)
Note that using (33), (41), and (12) we obtain the same transformation law (17) on a basis of the relation between entropy and partition function

\[ S = k \ln Z + \frac{U}{T}. \] (48)

4. LAWS OF THERMODYNAMICS AND ABSOLUTE SYNCHRONIZATION

We can easily check that the usual laws of statistical mechanics and thermodynamics are consistent with the transformation law of physical quantities derived in sections 2 and 3.

The transformation law for pressure (29) is consistent with the statistical definition of pressure

\[ P = kT \left( \frac{\partial \ln Z}{\partial V} \right)_T, \] (49)

provided the transformation laws for volume (22), partition function (35) and temperature (42) hold.

The form of the partition function of the perfect gas (44) and the above equation imply the relation

\[ PV = NkT, \] (50)

i.e. the usual Clapeyron’s equation of the state of the perfect gas.

Moreover, the relation \( P' = P \) agrees with the thermodynamical definition of pressure (Maxwell’s equation)

\[ P = -\left( \frac{\partial U}{\partial V} \right)_S. \] (51)

Maxwell’s equation for temperature is covariant in the absolute synchronization, too. Indeed, consider the relation

\[ T = \left( \frac{\partial U}{\partial S} \right)_V \] (52)

and use (11) and (17) to obtain \( T' = w_0 T \) again.

The above relation allows us to keep the first law of thermodynamics unchanged:

\[ dU = TdS - PdV. \] (53)

Therefore we can define the heat

\[ \delta Q = TdS \] (54)

and work

\[ \delta L = -PdV. \] (55)
Table I: Transformation laws for thermodynamical parameters using absolute synchronization; $w^0 = 1/\sqrt{1 + w^0 u \cdot v - (v)^2}$.

| Parameter            | Notation and definition | Transformation law |
|----------------------|-------------------------|-------------------|
| Volume               | $V$                     | $V' = w^0 V$      |
| Temperature          | $T$                     | $T' = w^0 T$      |
| Internal energy      | $U(S,V)$                | $U' = w^0 U$      |
| Enthalpy             | $H(S,P) = U + PV$       | $H' = w^0 H$      |
| Helmholtz free energy| $F(T,V) = U - TS$       | $F' = w^0 F$      |
| Gibbs’ free energy   | $G(T,P) = U - TS + PV$  | $G' = w^0 G$      |
| Pressure             | $P$                     | $P' = P$          |
| Entropy              | $S(U,V)$                | $S' = S$          |
| Partition function   | $Z(T,V)$                | $Z' = Z$          |
| Massieu’s potential  | $\Psi(1/T,V) = -F/T$    | $\Psi' = \Psi$   |
| Planck’s potential   | $\Phi(1/T,V) = -G/T$    | $\Phi' = \Phi$   |

Table II: Thermodynamical relations covariant under Lorentz group in absolute synchronization.

\[
U = kT^2 (\partial \ln Z / \partial T), \quad S = k \ln Z + U/T, \quad P = kT (\partial \ln Z / \partial V)_T, \\
P V = N k T, \quad P = - (\partial U / \partial V)_S, \quad T = (\partial U / \partial S)_V, \\
dU = T dS - P dV, \quad \delta Q = T dS, \quad \delta L = - P dV
\]

It is easy to check that $\delta Q' = w^0 \delta Q$ and $\delta L' = w^0 \delta L$.

Transformation laws for the thermodynamical parameters are collected in Table I. The fundamental thermodynamics relations that are covariant under Lorentz group in absolute synchronization scheme are shown in Table II.

5. CONCLUSIONS

In this paper we have formulated Lorentz-covariant thermodynamics. Such a formulation can be possible due to use of a preferred frame and absolute synchronization. As it was suggested in [3, 24, 21], the preferred frame can be possibly identified with the cosmic background radiation frame.

We have defined the distribution density and partition function that transforms covariantly under Lorentz boost in the framework of absolute synchronization. This is possible because the absolute synchronization allows for the existence of invariant measure on the phase space of a one-particle system. On this basis we derive transformation properties of all thermodynamical quantities, including entropy, temperature, internal energy and pressure. We can also
check that some basic thermodynamical relations such as thermodynamical relation for pressure, Maxwell’s relations, and Clapeyron’s equation are Lorentz covariant in the absolute synchronization scheme.

We would like to point out that, in contrary to the transformation laws found by Einstein, Planck and von Laue (7; 14) or the ones found by Ott and Arzelies (1; 16), the preferred frame approach allows one to find the transformation laws for thermodynamical quantities in any two inertial frames, not only between a given inertial frame and the system of center of mass of the gas. Moreover, it is easy to verify that in the simplest physical situations: (i) when the observer is in the preferred frame, and (ii) when the gas is in the preferred frame, the transformation law (42) becomes the Einstein–Planck law (1).

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