

# Predicting the density-scaling exponent of a glass-forming liquid from Prigogine-Defay ratio measurements

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## Abstract

Understanding the origin of the dramatic temperature and density dependence of the relaxation time of glass-forming liquids is a fundamental challenge in glass science. The recently established "density-scaling" relation quantifies the relative importance of temperature and density for the relaxation time in terms of a material-dependent exponent. We show that this exponent for approximate single-parameter liquids can be calculated from thermoviscoelastic linear-response data at a single state point, for instance an ambient-pressure state point. This prediction is confirmed for the van der Waals liquid tetramethyl-tetraphenyl-trisiloxane. Consistent with this, a compilation of literature data for the Prigogine-Defay ratio shows that van der Waals liquids and polymers are approximate single-parameter systems, whereas associated and network-forming liquids are not.

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Many liquids are known to exhibit peculiar, sometimes even spectacular behavior. Water is a notorious example with its many intriguing anomalies [1, 2]. This raises the questions: Do liquids exist with “simple” behavior and what characterizes such behavior? Based on theory and simulations recent papers [3–5] proposed such a class of liquids, “strongly correlating liquids”, which are approximate single-parameter liquids [6]. The possible existence of approximate single-parameter liquids [7–15] has important implications, particularly for solving long-standing fundamental questions related to the glass transition [16–20], but so far it has not been convincingly demonstrated in experiment.

In this paper we present an experimental test of a striking prediction for strongly correlating liquids, namely that the density-scaling exponent – characterizing how to scale density and temperature for different state points in order to have the relaxation times superpose onto a master curve [21–24] – may be calculated from equilibrium fluctuations at a single state point [5]. The equilibrium fluctuations are probed via the fluctuation-dissipation theorem, which relates linear-response functions to fluctuations. The experiments were performed on the van der Waals glass-forming liquid, tetramethyl-tetraphenyl-trisiloxane, which is a commercial silicone oil (DC704). The paper further presents a reinterpretation of the classical Prigogine-Defay ratio, showing that many other systems are strongly correlating, i.e., approximate single-parameter liquids. All together these results suggest that van der Waals liquids are strongly correlating, confirming the long-held, general view that these are simpler than associated liquids. In contrast, network-forming liquids like water, glycerol, or silica are much more complex.

Temperature and volume both play important roles for the viscous slowing down as the glass transition is approached from above [25, 26]. The first measurements of viscosity under high pressure were published in 1949 by Bridgman [27], but only during the last decade has a substantial amount of data become available on the dynamics of viscous liquids at different pressures. The information comes mainly from dielectric spectroscopy, but inelastic neutron scattering and other experiments have also been performed under pressure (Ref. 24 reviews the dynamics of glass-forming liquids under hydrostatic pressure). The most important experimental finding from high-pressure studies of liquid dynamics is probably *density scaling*, i.e., the fact that the temperature ( $T$ ) and density ( $\rho$ ) dependences of the relaxation time for many liquids can be described in terms of the single scaling variable  $\rho^{\gamma_{\text{scale}}} / T$  [21–24], where  $\gamma_{\text{scale}}$  is the so-called density-scaling

exponent. Density scaling applies, e.g., for van der Waals liquids, but not for hydrogen-bonded liquids [28].

A simple explanation of density scaling can be given for strongly correlating liquids. These are characterized by near proportionality between the isochoric thermal equilibrium fluctuations of the virial  $W$  and the potential energy  $U$  [3–5], the quantities that give the configurational parts of pressure and energy, respectively. That is,  $W$  and  $U$  are the terms which are added to the kinetic ideal gas terms resulting from the molecular interactions. The total energy  $E$  is the kinetic energy  $K$  plus the potential energy  $U$ , and the pressure  $p$  is likewise an ideal gas term  $Nk_B T/V$  plus the configurational part  $W/V$ :

$$E = K + U \quad (1)$$

$$pV = Nk_B T + W \quad (2)$$

Here  $V$  is the volume and  $N$  the number of particles. Both the virial and the potential energy fluctuate around their equilibrium values. At any given time the fluctuations are defined by  $\Delta W(t) = W(t) - \langle W \rangle$  and  $\Delta U(t) = U(t) - \langle U \rangle$  ( $\Delta$  is here used in the standard meaning of statistical mechanics, whereas in the Prigogine-Defay ratio literature  $\Delta$  denotes the difference between liquid and glass properties).

A strongly correlating liquid has “isomorphs”, which are curves in the phase diagram along which a number of properties in reduced units – including the dynamics – are invariant [5]. The isomorph concept implies density scaling: A strongly correlating liquid’s isomorphs obey the equation  $\rho^{\gamma_{\text{isom}}}/T = \text{Const.}$ , where  $\gamma_{\text{isom}}$  is determined from the isochoric equilibrium fluctuations’ near proportionality between virial and potential energy fluctuations,  $\Delta W(t) \cong \gamma_{\text{isom}} \Delta U(t)$  [5]. In particular, the reduced-unit relaxation time is a function of  $\rho^{\gamma_{\text{isom}}}/T$ . The predicted equality of the fluctuation exponent  $\gamma_{\text{isom}}$  and the density-scaling exponent  $\gamma_{\text{scale}}$  has been verified for a few computer-simulated liquids [29, 30], but never tested experimentally. Such a test is very demanding, however, because it involves new and unique measurements of several frequency-dependent thermoviscoelastic response functions.

In this work we present the first test of this type. In order to do so we have chosen a liquid expected to be strongly correlating. It is known computer from simulations and theoretical considerations that liquids with simple Lenard Jones like interactions are strongly

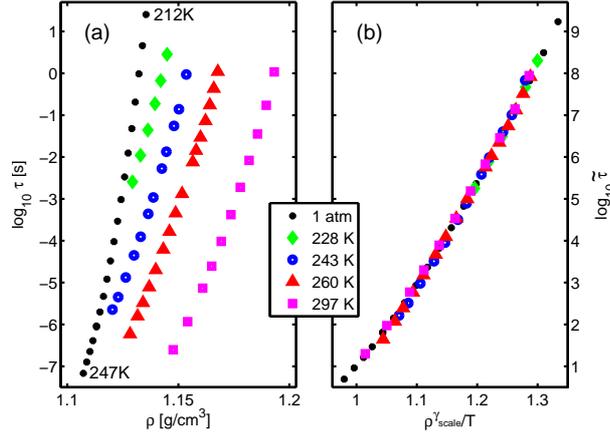


FIG. 1: The dielectric relaxation time  $\tau$  measured along different isotherms and along the atmospheric pressure isobar for the silicone oil DC704. The points come from measured loss peaks and the relaxation times refer to inverse angular loss-peak frequencies. (a) The relaxation times as functions of density (calculated from measured pVT-data). (b) The reduced unit relaxation time,  $\tilde{\tau} = C\rho^{1/3}T^{1/2}\tau$ , as a function of  $K\rho^{\gamma_{\text{scale}}}/T$ , where  $\gamma_{\text{scale}} = 6.2 \pm 0.2$  is a parameter adjusted to collapse the data of (a).  $C$  and  $K$  are constants which have no influence on the quality of the scaling, they only shift the axes.

correlating, while liquids with directional bonds (eg. hydrogen bonds) are not [3–5]. This is consistent with the experimental finding that van der Waals bonded liquids obey density scaling, whereas hydrogen-bonded liquids do not. Yet it is important to keep in mind that strong correlation implies density scaling, while the opposite is not necessarily true. Density scaling might well hold for a larger class of liquids. The  $\gamma_{\text{isom}} = \gamma_{\text{scale}}$  prediction, however, is only expected to hold for strongly correlating liquids.

As our test sample we have chosen the van der Waals glass-forming liquid tetramethyl-tetraphenyl-trisiloxane (DC704). We expect it to be strongly correlating because it has a very low dipole moment, which means that it is truly van der Waals bonded, yet the dipole moment is large enough to give a good signal in the high-pressure dielectric measurements. DC704 is moreover chemically very stable and an excellent glass former.

Figure 1 (a) shows the dielectric relaxation time, defined as the inverse angular frequency of the loss peak position, for DC704 as a function of density for different isotherms, as well as data taken at atmospheric pressure. pVT-data were used to calculate

the density at each state point. Density scaling is demonstrated in Fig. 1 (b), showing that all data collapse onto a master curve when the reduced-unit relaxation time is plotted as a function of the scaling variable  $\rho^{\gamma_{\text{scale}}}/T$ . The  $\gamma_{\text{scale}} = 6.2 \pm 0.2$  is an empirical fit parameter and the reduced-unit relaxation time  $\tilde{\tau}$  is given by  $\tilde{\tau} = C\rho^{1/3}T^{1/2}\tau$  where  $C$  is an arbitrary constant with no influence on the scaling (it only changes the numbers on the y-axis). The use of reduced units is theoretically correct, but the actual difference between using reduced units or absolute values is minimal in the supercooled region because the relaxation times vary over many orders of magnitude, while  $T$  only changes 30% and  $\rho$  even less. In fact, when we perform the scaling using absolute values of  $\tau$  we arrive at  $\gamma_{\text{scale}} = 6.1 \pm 0.2$ .

Turning now to the isomorph prediction, the near proportionality of the equilibrium fluctuations,  $\Delta W(t) \cong \gamma_{\text{isom}}\Delta U(t)$ , is consistent with the theoretical expression for  $\gamma_{\text{isom}}$  (the sharp brackets denote  $NVT$  ensemble averages) [5]

$$\gamma_{\text{isom}} = \frac{\langle \Delta W \Delta U \rangle}{\langle (\Delta U)^2 \rangle}. \quad (3)$$

In order to calculate this quantity from linear thermoviscoelastic measurements we reason as follows. A characteristic feature of viscous liquids is time-scale separation. Fluctuations of the kinetic terms decorrelate on a picosecond time scale. Consequently, if one averages the fluctuations in pressure and energy over a time scale much longer than picoseconds but much shorter than the liquid's relaxation time, one gets the fluctuations of the configurational terms. For such averages it follows that  $\langle \Delta W \Delta U \rangle / \langle (\Delta U)^2 \rangle \cong V \langle \Delta p \Delta E \rangle / \langle (\Delta E)^2 \rangle$ . This brings us closer to something that can be accessed experimentally, because fluctuations in pressure and energy determine the thermoviscoelastic linear-response functions via the fluctuation-dissipation theorem:  $V \langle \Delta p \Delta E \rangle / \langle (\Delta E)^2 \rangle = (\beta_V^{\text{slow}} - \beta_V^{\text{fast}}) / (c_V^{\text{slow}} - c_V^{\text{fast}})$ , where  $\beta_V = (\partial p / \partial T)_V$  is the pressure coefficient and  $c_V$  the isochoric specific heat per unit volume. Here "slow" response means the long-time (low-frequency) liquid-like limit, and "fast" response means the short-time (high-frequency) solid-like limit of the relevant (complex) frequency-dependent linear-response function of the equilibrium liquid, still probing the system at times much longer than phonon times. Thus

$$\gamma_{\text{isom}} = \frac{\beta_V(\omega \rightarrow 0) - \beta_V(\omega \rightarrow \infty)}{c_V(\omega \rightarrow 0) - c_V(\omega \rightarrow \infty)}. \quad (4)$$

The high-frequency values ( $\omega \rightarrow \infty$ ) correspond to solid-like responses, where the liquid has time to explore only one potential energy minimum, a so-called inherent state. This implies that  $\gamma_{\text{isom}}$ , as discussed later, can be evaluated approximately using the much easier measured values for the glassy state instead of the high-frequency values [4, 31].

The two linear thermoviscoelastic response functions  $\beta_V(\omega)$  and  $c_V(\omega)$  refer to constant-volume measurements; however, experiments are usually performed under constant pressure. This problem can be overcome by measuring three independent thermoviscoelastic response functions and subsequently calculating  $\beta_V(\omega)$  and  $c_V(\omega)$  using standard thermodynamic relations. These relations include dynamic versions of the Maxwell relations, which are the so-called generalized Onsager reciprocity relations reflecting the time reversibility of the underlying microscopic equations of motion [32]. Unfortunately, even constant-pressure conditions are difficult to attain for ultra-viscous liquids because thermal expansion is often limited in some directions, leading to significant shear stresses in the sample [33]. This implies that  $c_p(\omega)$  is not measured directly; rather it is the “longitudinal” dynamic heat capacity  $c_l(\omega)$  that is measured in most experiments [33]; similarly for thermal expansion we measure the dynamic longitudinal expansion coefficient  $\alpha_l(\omega)$ , rather than the dynamic isobaric expansion coefficient  $\alpha_p(\omega)$  [34]. Fortunately, knowledge of the shear modulus  $G(\omega)$  allows one to calculate  $c_p(\omega)$  and the isobaric expansion coefficient  $\alpha_p(\omega)$  from data (see Eq. (5) below). In summary, to determine the predicted density-scaling exponent  $\gamma_{\text{isom}}$  we measured the following four complex dynamic linear thermoviscoelastic response functions: the adiabatic compressibility  $\kappa_s(\omega)$ , the longitudinal heat capacity  $c_l(\omega)$ , the longitudinal expansion coefficient  $\alpha_l(\omega)$ , and the shear modulus  $G(\omega)$ .

The dynamic shear modulus  $G(\omega)$  was measured using a piezoceramic transducer [35], the dynamic adiabatic compressibility  $\kappa_s(\omega)$  by a similar technique [36], and the dynamic longitudinal heat capacity  $c_l(\omega)$  was measured using the  $3\omega$ -method [37] in a spherical geometry [38]. The dynamic longitudinal expansion coefficient  $\alpha_l(\omega)$  was calculated via a Laplace transform of a signal measured in the time domain using capacitive dilatometry [34, 39] (more details on all methods are given in the Methods section).

Examples of the measured complex, dynamic linear-response functions are shown in Fig. 2. In principle, we need only data at one state point to determine  $\gamma_{\text{isom}}$  from Eq. (4). In practice, we used several temperatures to estimate reliably the temperature depen-

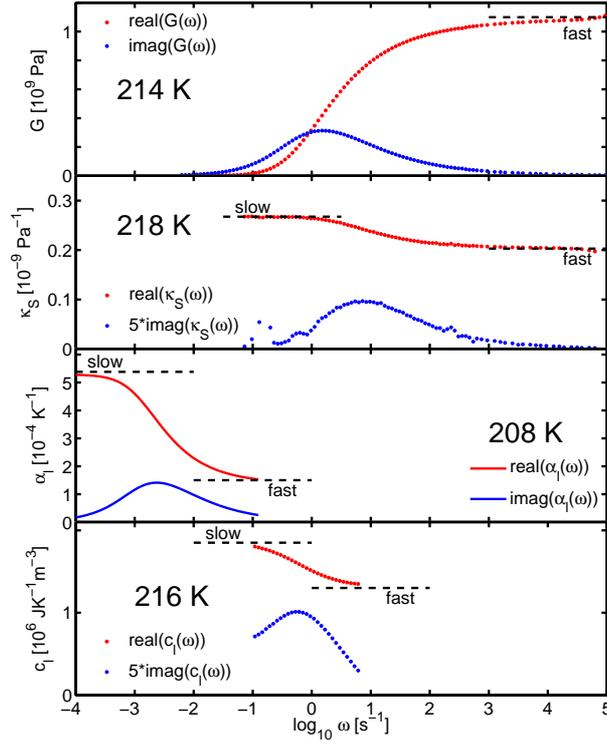


FIG. 2: Examples of frequency-dependent real and imaginary parts of the four required thermo-viscoelastic response functions of DC704, illustrating the experimental challenges associated with checking the isomorph prediction  $\gamma_{\text{scale}} = \gamma_{\text{isom}}$ . The experimental techniques work in different frequency intervals (see the Methods section); in order to place the relaxation region central in the accessible frequency window for each technique we show data at temperatures that vary with response function. (a) The shear modulus  $G(\omega)$ . (b) The adiabatic compressibility  $\kappa_S(\omega)$ . (c) The longitudinal expansion coefficient  $\alpha_l(\omega)$ , for which data were measured in the time domain and subsequently converted to the frequency representation via a numerical Laplace transform [34]. (d) The longitudinal heat capacity  $c_l(\omega)$ .

dence of the short-time and long-time levels. This was done in order to be able to extrapolate the DC704 expansion coefficient, which was obtained at lower temperatures than the other response functions (see the Methods section). The temperature 214 K is close to the calorimetric glass transition temperature of DC704, but it should be emphasized that all measurements refer to the linear response of the equilibrium liquid, a state that needs careful annealing to be reached, particularly at our lowest temperatures. The relevant values of  $\beta_V(\omega)$  and  $c_V(\omega)$  were calculated from the high- and low-frequency limits

of the four measured thermoviscoelastic response functions, respectively, by solving the following four equations with four unknowns:

$$\begin{aligned}
c_l(\omega) &= \frac{1 + (4/3)G(\omega)\kappa_S(\omega)}{1 + (4/3)G(\omega)\kappa_T(\omega)}c_p(\omega) \\
\alpha_l(\omega) &= \frac{\alpha_p(\omega)}{1 + (4/3)G(\omega)\kappa_T(\omega)} \\
c_V(\omega) &= c_p(\omega) - \frac{T(\alpha_p(\omega))^2}{\kappa_T(\omega)} \\
\kappa_S(\omega) &= \frac{c_V(\omega)\kappa_T(\omega)}{c_p(\omega)}
\end{aligned} \tag{5}$$

and using the relation  $\beta_V(\omega) = \alpha_p(\omega)/\kappa_T(\omega)$ . The values of the measured short- and long-time levels at the reference temperature are reported in Tab. I. When substituted into Eq. (4) we find that the isomorph prediction for the density-scaling exponent of DC704 is  $\gamma_{\text{isom}} = 6 \pm 2$ , which is in good agreement with the experimental density-scaling exponent  $\gamma_{\text{scale}}=6.2 \pm 0.2$  (Fig. 1(b)). The large uncertainty of  $\gamma_{\text{isom}}$  derives from the fact that measuring the absolute values of the frequency-dependent thermoviscoelastic response functions is very challenging. Even considering the large uncertainty in the predicted  $\gamma_{\text{isom}}$ , it is striking that  $\gamma_{\text{isom}}$  agrees with the exponent from density scaling. This agreement shows that for DC 704 thermoviscoelastic linear-response measurements at one ambient-pressure state point can be used to predict the density-scaling exponent, which describes the density and temperature dependence of relaxation times varying from micro- to kilo-seconds, measured at pressures up to 400 MPa over a 90 K temperature range. This is a main conclusion of the present paper.

The correlation coefficient between  $W$  and  $U$  in the  $NVT$  ensemble,

$$R = \frac{\langle \Delta W \Delta U \rangle}{\sqrt{\langle (\Delta U)^2 \rangle \langle (\Delta W)^2 \rangle}}, \tag{6}$$

measures how strong the virial / potential energy correlations are in a liquid ( $-1 \leq R \leq 1$ ; the closer  $R$  is to unity, the better correlation). It therefore provides a measure of how well a liquid is expected to follow the isomorph theory. Expressing  $R$  in terms of linear-response functions, it becomes clear that  $R$  is given directly by the linear  $NVT$  Prigogine-Defay (PD) ratio [6],  $\Pi_{VT}^{\text{lin}}$ :

$$R = \frac{\beta_V^{\text{slow}} - \beta_V^{\text{fast}}}{\sqrt{-(K_T^{\text{slow}} - K_T^{\text{fast}})(c_V^{\text{slow}} - c_V^{\text{fast}})/T}} = \frac{1}{\sqrt{\Pi_{VT}^{\text{lin}}}}. \tag{7}$$

DC704 (214 K)	
$c_l^{\text{slow}} [10^6 \text{J}/(\text{K m}^3)]$	$1.65 \pm 0.15$
$c_l^{\text{fast}} [10^6 \text{J}/(\text{K m}^3)]$	$1.35 \pm 0.05$
$\kappa_S^{\text{slow}} [10^{-9} \text{Pa}^{-1}]$	$0.25 \pm 0.03$
$\kappa_S^{\text{fast}} [10^{-9} \text{Pa}^{-1}]$	$0.19 \pm 0.03$
$\alpha_l^{\text{slow}} [10^{-3} \text{K}^{-1}]$	$0.46 \pm 0.04$
$\alpha_l^{\text{fast}} [10^{-3} \text{K}^{-1}]$	$0.11 \pm 0.01$
$G^{\text{slow}} [10^9 \text{Pa}]$	0
$G^{\text{fast}} [10^9 \text{Pa}]$	$1.1 \pm 0.05$
$\Pi_{pT}^{\text{lin}}$	$1.1 \pm 0.3$
$\Pi_{VT}^{\text{lin}}$	$1.2 \pm 0.6$
$R$	$0.9 \pm 0.2$
$\gamma_{\text{isom}}$	$6 \pm 2$
$\gamma_{\text{scale}}$	$6.2 \pm 0.2$

TABLE I: The values of measured short-time (“fast”) and long-time (“slow”) levels of the four thermoviscoelastic response functions of DC704 at 214 K. These data were used to calculate the exponent  $\gamma_{\text{isom}}$  predicted to be equal to  $\gamma_{\text{scale}}$ . The error bars on the measured data reflect max-min values, the errors bars on the calculated values were identified using standard error propagation techniques.

Here  $K_T = 1/\kappa_T$  is the isothermal bulk modulus. The PD ratio equals unity if the liquid is a single-parameter liquid [7–15]. Thus, a perfectly correlating liquid is what was traditionally referred to as a single-parameter liquid [6]. Earlier studies of the PD ratio gave no physical interpretation of values different from one, even if these were close to one. The above interpretation of the linear NVT PD ratio as given by the correlation coefficient shows that the PD ratio provides a measure of how strongly correlating a given liquid is.

When the linear  $NVT$  PD ratio is exactly unity, other linear PD ratios, e.g., the experimentally relevant linear  $NpT$  PD ratio, are also unity [6]. When  $\Pi_{VT}^{\text{lin}}$  is not strictly one, there is no such result, but by continuity we surmise that  $\Pi_{pT}^{\text{lin}}$  is close to unity if and only if  $\Pi_{VT}^{\text{lin}}$  is. For DC704 we find  $\Pi_{pT}^{\text{lin}} = 1.1 \pm 0.3$  and  $\Pi_{VT}^{\text{lin}} = 1.2 \pm 0.6$ , which is consistent

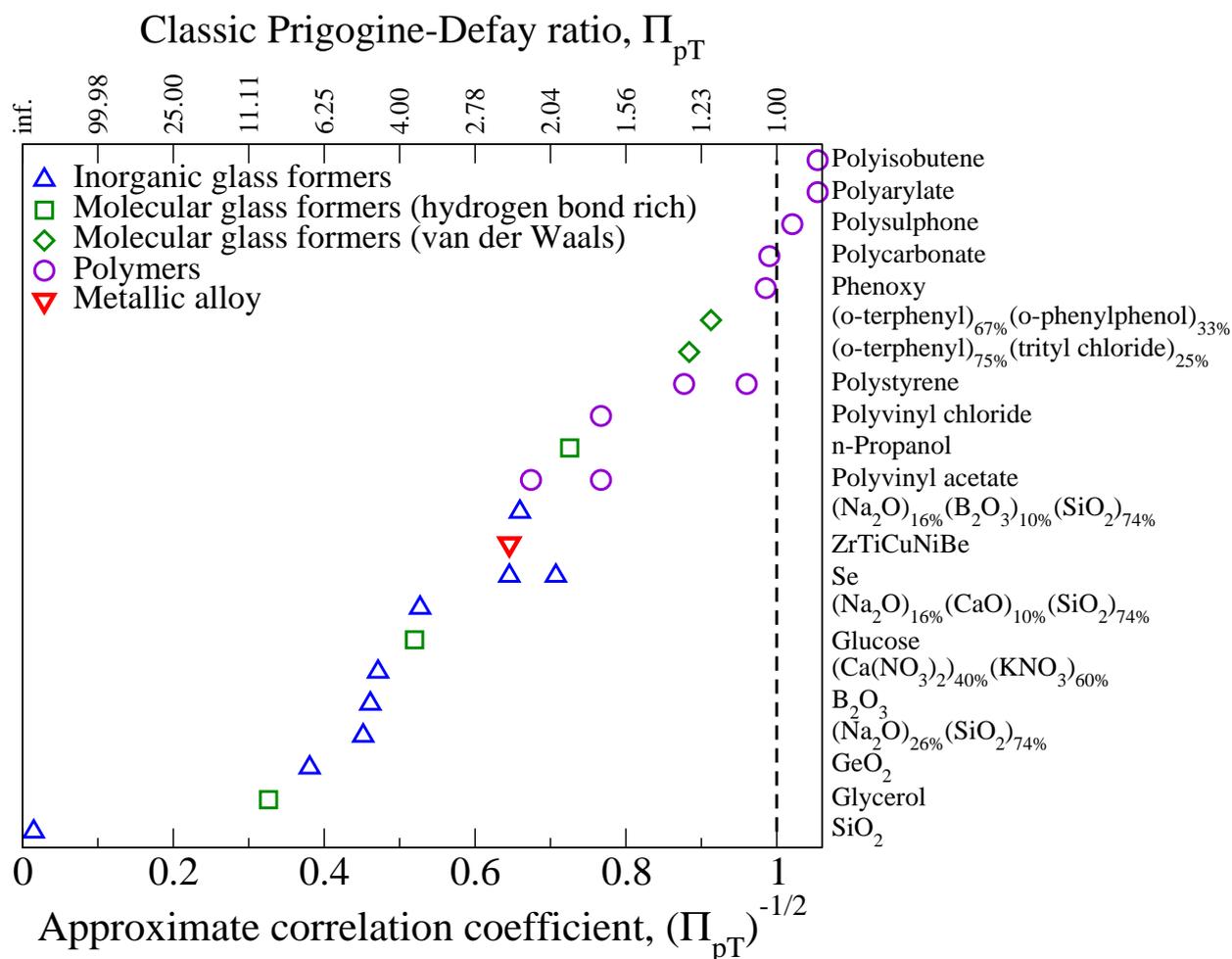


FIG. 3: Literature values of the classical ( $NpT$ ) Prigogine-Defay (PD) ratios  $\Pi_{pT}^{\text{classic}}$  of 22 glass formers. The liquids, which are sorted according to reported value of the PD ratio, include inorganic glass formers (triangles pointing up), hydrogen-bond-rich molecular liquids (squares), van der Waals molecular liquids (diamonds), polymers (circles), and a metallic alloy (triangle pointing down). The inverse squareroot of the classical  $NpT$  Prigogine-Defay ratio gives an estimate for the correlation coefficient (lower x-axis). Strong correlations are found in van der Waals bonded molecular liquids and polymers (the Supplementary information provides the PD values shown in the figure and relevant references; note that each symbol in the figure corresponds to the liquid listed to the right).

with this conjecture.

Whereas neither the linear  $NVT$  PD ratio nor the linear  $NpT$  PD ratio have been reported in the literature prior to this study, there are many reports on the classical ( $NpT$ )

PD ratio. This quantity is calculated using temperature-extrapolated liquid and glassy static responses, where the glassy response is defined from the low-temperature ( $T < T_g$ ) solid response:

$$\Pi_{pT}^{\text{classic}} \equiv \frac{(\kappa_T^{\text{liq}}(T_g) - \kappa_T^{\text{glass}}(T_g))(c_p^{\text{liq}}(T_g) - c_p^{\text{glass}}(T_g))}{T_g(\alpha_p^{\text{liq}}(T_g) - \alpha_p^{\text{glass}}(T_g))^2}. \quad (8)$$

Here " $T_g$ " indicates the extrapolation to the glass transition temperature. The classical PD ratio involves extrapolations and is therefore not rigorously well-defined [6, 10, 40, 41]. Moreover, the glassy response depends on how the glass is made, e.g., the cooling rate, which means that different protocols might well result in somewhat different values of the PD ratio. Nevertheless, the classical PD ratio provides an experimentally much easier route for estimating the degree of  $WU$  correlation than measuring the proper frequency-dependent linear thermoviscoelastic response functions at one temperature. In the absence of linear PD ratio data we compiled all the literature data we could find on the classical PD ratio.

Figure 3 shows the PD values for 22 glass formers, including polymers, a metallic alloy, inorganic and molecular liquids (both hydrogen-bond rich and van der Waals bonded). The systems have been sorted according to their PD ratio. In analogy with the  $NVT$  case, we define an approximate correlation coefficient of the  $NpT$  ensemble as the inverse square-root of the  $NpT$  PD ratio. Network-bonded inorganic glass formers such as silica glasses and hydrogen-bond rich molecular liquids (e.g., glycerol and glucose) have large PD ratios. In contrast, van der Waals liquids, exemplified by the polymers and the two mixtures with *o*-terphenyl as the major constituent, have PD ratios close to one. This confirms the conjecture that van der Waals liquids are strongly correlating, whereas associated and network-forming liquids are not [4, 5]. It is also interesting to compare propanol and glycerol, which have the same backbone of three carbon atoms, but one and three hydroxyl groups, respectively. Propanol with only one hydroxyl group and therefore fewer hydrogen bonds has a considerably smaller PD ratio than glycerol. The pattern in Fig. 3 is consistent with computer simulation results, where liquids without directional bonding or competing interactions are generally found to be strongly correlating [4, 5].

The glassy and liquid extrapolated response values used to calculate the classical PD

ratio provide an alternative, but less well-defined way of calculating  $\gamma_{\text{isom}}$ <sup>1</sup>. We did the analysis on the data of a mixture 67% o-terphenyl and 33% o-phenylphenol from a paper by Takahara *et al.*[42]. This mixture is a strongly correlating liquid with  $\Pi_{pT}^{\text{classic}} = 1.20$  [42]. We find  $\gamma_{\text{isom}} = 5.4 \pm 1$ , which is to be compared to the density-scaling exponent for this liquid  $\gamma_{\text{scale}} = 6.2 \pm 0.2$  [24]. This is consistent with the isomorph prediction (see the Supplementary information for details).

We have argued that the PD ratio of a large class of liquids should be regarded as essentially equal to unity. The general consensus, however, is that unity PD ratios are rare exceptions or not allowed (see, e.g., Refs. [42–44]). In recent years, several studies have been dedicated to understanding non-unity PD ratios. These approaches can be summarized as follows: (1) Linear-response theories of thermoviscoelasticity yielding non-unity ratios for systems with more than one internal state variables [6, 13, 45, 46]; (2) A non-equilibrium thermodynamic theory explaining non-unity of the classical PD ratio as a non-equilibrium effect (even in the case of a single internal state variable) [43]; (3) A Landau theory using nano-thermodynamics where dynamical heterogeneity is the origin of non-unity PD ratios [47]. In this paper we adopted the first viewpoint, which is the original rigorous linear PD ratio interpretation going back to the seminal works by Moynihan and coworkers more than 30 years ago [10, 48].

Our findings show that strongly correlating liquids exist not merely in computer simulations, but also as real liquids. These liquids are simpler than liquids in general, while still having all the hallmarks of viscous slowing down upon supercooling, eventually leading to a glass transition. For strongly correlating liquids there is an “isomorph filter” [5] according to which theories for the non-Arrhenius temperature dependence of the relaxation time can be sorted: Only theories that express the relaxation time in terms of an isomorph invariant can be correct for strongly correlating liquids and thus be of general validity. Moreover, strongly correlating liquids several phenomena can be explained in simple terms on the basis of the existence of isomorphs in the liquid’s phase diagram [5]. Examples include isochronal superposition (i.e., the finding that dielectric loss spectra under varying pressure and temperature are invariant for states with the

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<sup>1</sup> This type of expression for  $\gamma_{\text{scale}}$  was also found in Ref. [31] by using an entropy-based model for the dynamics.

same relaxation time), and aging behavior after temperature and pressure jumps [5, 49]. These phenomena are well understood for perfectly correlating liquids, and liquids with strong correlations inherit the behavior to a good approximation. The degree to which these phenomena survive as the correlation gets poorer is a cardinal point for further research; it is likely that some predictions are more sensitive to deviations from perfect correlation than others. We suggest that the class of perfectly correlating liquids should be regarded as “ideal gas” or “Ising models” of liquids - that is, simple systems for which a number of generic features of the glass transition phenomenology can be understood. In this way, the identification of what constitutes a “simple” liquid will hopefully lead to a better general understanding of viscous liquids and the glass transition.

## I. METHODS

The liquid studied, the Dow Corning diffusion pump silicone oil tetramethyl-tetraphenyl-trisiloxane DC704, was used as received without further purification. The different measurements (in total six different experiments) were performed on a sample taken from the same bottle – and DC704 is not hygroscopic so water contamination is not a problem. Moreover, the pVT measurements and the high pressure dielectric spectroscopy measurements used to determine  $\gamma$  were performed in the same lab and by the same team. For all these reasons we are fairly confident by the scaling  $\gamma$  of DC 704 reported in the paper; the uncertainties are much larger for the isomorph  $\gamma$ .

The thermoviscoelastic linear-response techniques utilize a custom-built cryostat [50].  $G(\omega)$ ,  $\kappa_S(\omega)$  and  $c_l(\omega)$  were measured in the same cryostat;  $\alpha_l(\omega)$  was obtained from measurements in the same type of cryostat and the temperatures were calibrated with dielectric spectra taken on the DC704-sample, ensuring that the absolute temperatures were the same for all measurements.

The shear modulus  $G(\omega)$  is measured over the frequency range  $10^{-3}$ – $10^4$  Hz [35], and the adiabatic compressibility  $\kappa_S(\omega)$  is measured over  $10^{-2}$ – $10^4$  Hz [36]. Both methods are optimized for measurements on very stiff materials (modulus ranges of MPa–GPa) and are based on piezoceramic materials that act as converters of mechanical properties into electrical properties.

The measurements of specific heat were done by a  $3\omega$  thermal-effusion method in

spherical geometry [38], a technique which is equivalent to the planar plate  $3\omega$  technique of Birge and Nagel [37], however utilizing a spherical thermistor bead instead of a thin planar metal film. It covers a frequency range of  $10^{-2.5}$ – $10^{0.5}$  Hz, limited by the intrinsic frequency dependence of the thermal impedance in this geometry. The isobaric specific heat,  $c_p(\omega) = (\kappa_T(\omega)/\kappa_S(\omega))c_V(\omega)$  is not measured in this geometry; rather what is measured is the longitudinal specific heat,  $c_l(\omega) = (M_S(\omega)/M_T(\omega))c_V(\omega)$  (where  $M(\omega)$  represents longitudinal moduli) [38].

The measurements of the longitudinal thermal expansion coefficient in the time domain  $\alpha_l(t)$  were carried out utilizing a microregulator [34, 50] allowing for fast temperature changes of a small planar capacitor. This technique is based on a temperature-step variant of “capacitive scanning dilatometry” [39], which utilizes the fact that the capacitance of a capacitor is inversely proportional to the thickness of the liquid in the capacitor. What is measured in this geometry is the longitudinal thermal expansion coefficient  $\alpha_l$  (see Eq. 5) [33]. The dynamic longitudinal expansion coefficient  $\alpha_l(\omega)$  shown in figure 2 was calculated via a Laplace transform of a signal measured in the time domain. However, Eq. 4 requires only knowledge of the high and low-frequency limits of the response functions and the required limits for  $\alpha_l(\omega)$  were obtained directly from the data measured in the time domain (as short and long-time limits respectively) i.a., without Laplace transforming.

The heat capacity is the response function for which data are measured over the narrowest frequency (and therefore also temperature) range. The studied temperature range was 214-218 K and within the experimental uncertainties there is no temperature dependence of the slow and fast values. We chose 214 K as the reference temperature in order to minimize the extrapolation required of the expansion coefficient data, which were measured in the 204 – 210 K range.

Note that all data were taken in thermal equilibrium, a state it takes careful annealing to reach at low temperatures.

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### III. AUTHOR CONTRIBUTIONS

URP and KN conceived the project. DG, URP, BJ, JCD, and KN wrote the paper with input from CMR. DG, URP, and KN did the main data analysis. TH measured the shear modulus and compressibility and did the raw data analysis. BJ and TC measured the heat capacity and did the raw data analysis. KN measured the expansion coefficient and did the raw data analysis. TC and NBO conceived and developed the four thermoviscoelastic measuring techniques used. DG, DF, and RC measured the high-pressure data and did the scaling data analysis. URP, NPB, TC, TBS, and JCD supplied the theoretical background for the project, which was coordinated by KN.

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