

Isomerization and inherent structures in liquids. A molecular dynamics study of liquid cyclohexane

Jonathan G. Harris^{a)} and Frank H. Stillinger
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

(Received 11 March 1991; accepted 12 July 1991)

The effect of conformational isomerization on liquid structure has been examined, using a realistic model of cyclohexane as an example. Molecular dynamics simulations at 300 K and 1 atm have been carried out for two liquid samples: one consisted of an all-chair medium, the other was prepared with about half of the molecules trapped in the twisted-boat form. During each molecular dynamics run, sets of liquid phase configurations were mapped onto representative potential energy minima (inherent structures) by a steepest-descent procedure. Comparison of distribution functions before and after this configurational mapping shows that thermal motions strongly obscure the effects of chair, twisted-boat isomerization on local liquid order, though such effects are clearly present in the inherent structures. The latter contain resolved characteristic intramolecular and intermolecular distance distributions that should be observable in low temperature amorphous deposits of cyclohexane.

I. INTRODUCTION

The local structure and the macroscopic observable properties of liquids are determined by the interactions operative within the collection of molecules involved. These interactions normally can be represented by a potential energy function $\Phi(\mathbf{R})$ that comprises both intramolecular and intermolecular portions. By examining details of the Φ hypersurface in the space of system configurations \mathbf{R} , one can hope to learn about the source of static structural attributes and the mechanisms of various rate processes in the liquid.

Stillinger and Weber¹⁻⁵ have previously introduced the concept of "inherent structures" for condensed phases (i.e., the discrete set of configurations corresponding to local Φ minima) and have employed these fiducial states to probe attributes such as crystallization, vitrification, and chemical reactivity. In the present work we apply the inherent structure analysis to the study of conformational isomerism in molecular liquids, specifically liquid cyclohexane.

Many organic molecules can exist in several conformational states that are separated by high intramolecular potential energy barriers. The crossing of these barriers typically requires concerted rotations about one or more chemical bonds. Cyclohexane provides a prominent example, with chair and twisted-boat configurations illustrated, respectively, by Figs. 1 and 2. The chair isomer is more stable than the twisted boat by 23 kJ/mol.⁶ Conversion of chair to twisted boat requires surmounting a 48 kJ/mol barrier.⁷

The Stillinger-Weber inherent structure approach distinguishes two fundamental contributions to local order in liquids, the purely packing part corresponding to the local potential energy minima for the system as a whole, and the thermally excited (and possibly very anharmonic) vibrational excursions away from those local minima. The vibrational deformations obscure intrinsic order; in the case of

chemically reactive media this obscuring effect can make it difficult to identify which distinct chemical species are present. However, mapping configurations onto the minima (inherent structures) has been found to resolve the ambiguity.⁸⁻¹³ In part the present project was motivated by the suspicion that mapping onto potential energy minima would produce a similar clarification in the case of molecular isomerization, which is after all a specific kind of unimolecular reaction. As explained below, this expectation has indeed been confirmed.

To the best of our knowledge, the present work is the first application of the inherent structure approach to isomerization in organic liquids. We examine below the local structures in liquid samples containing, respectively, an all-chair-form collection of molecules (the expected form at room temperature), and a liquid mixture with approximately equal numbers of chair and of twisted-boat isomers. On the conventional laboratory time scale the room-temperature conversion rate of twisted chair to boat is too high to allow convenient measurements on the equimolar mixture, but such interconversion is very slow indeed on our molecular dynamics time scale.

Section II outlines the inherent structure formalism for completeness. Section III explains details of our cyclohexane model and presents the molecular dynamics methodology. Section IV contains results from the simulation for both the liquid states investigated and for the collections of inherent structures obtained therefrom. The final Sec. V discusses these results and their implications.

II. INHERENT STRUCTURE THEORY

The central concept of inherent structure theory is the many-to-one mapping of system configurations \mathbf{R} onto those of the local Φ minima, \mathbf{R}_α . This mapping is generated as $s \rightarrow +\infty$ by solutions to the mass-weighted relaxation equations¹⁴

^{a)} Present address: Department of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

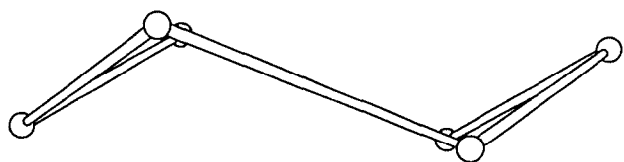


FIG. 1. Chair-form isomer of cyclohexane.

$$\mathbf{M} \cdot \frac{d\mathbf{R}}{ds} = -\nabla_{\mathbf{R}} \Phi(\mathbf{R}) \quad (0 \leq s), \quad (2.1)$$

which invariably descend on the Φ hypersurface. Here \mathbf{M} is the diagonal matrix of particle masses, and $\mathbf{R}(s=0)$ is the configuration to be mapped. Only a zero-measure (and thus negligible) set of initial configurations fail to descend to local Φ minima by this scheme, lodging instead at saddle points of various orders.

The set of all configurations that map onto a given minimum α defines a connected "basin" B_α containing that minimum. The collection of such basins exhausts the available configuration space without overlaps, and therefore provides a natural partitioning of that configuration space. The canonical configurational partition function for N identical molecules, e.g.,

$$Z_N(\beta) = (N!)^{-1} \int d\mathbf{R} \exp[-\beta\Phi(\mathbf{R})],$$

$$\beta = (k_B T)^{-1}, \quad (2.2)$$

can be recast exactly as a sum over basin partition functions^{1-5,14}

$$Z_N(\beta) = \sum_{\alpha} \exp(-\beta\Phi_{\alpha}) \int_{B_{\alpha}} d\mathbf{R} \exp[-\beta\Delta_{\alpha}\Phi(\mathbf{R})],$$

$$\Phi_{\alpha} = \Phi(\mathbf{R}_{\alpha}),$$

$$\Delta_{\alpha}\Phi(\mathbf{R}) = \Phi(\mathbf{R}) - \Phi_{\alpha}. \quad (2.3)$$

The α sum in this last expression includes only distinct basins, i.e., those not related by permutation of identical particles. By definition, vibrational motions about any inherent structure (Φ local minimum) are limited in amplitude by the boundaries of the corresponding basin.

In the event that the N molecules comprising the system each can adopt n distinguishable conformational isomers, the Φ minima can be classified by the $n-1$ independent mole fractions of each such species. For the case of cyclohexane $n=2$, leaving a single scalar order parameter to measure

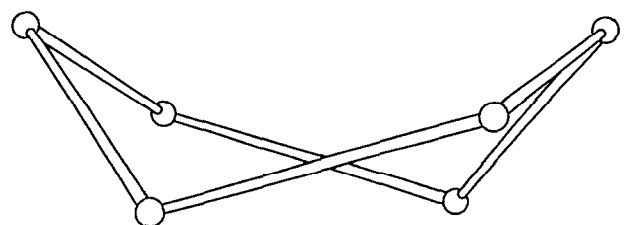


FIG. 2. Twisted-boat isomer of cyclohexane.

the conformational composition for each minimum. As remarked above this order parameter relaxes very slowly on the molecular dynamics time scale.

III. MODEL AND METHODS

For the sake of computational economy we have used a united atom view of cyclohexane. That is, each methylene unit CH_2 is treated as a single force center with appropriate mass, six such units comprising each molecule. As a result the total system potential has the following form:

$$\Phi(\mathbf{R}) = \sum'_{i < j} v(r_{ij}) + \sum_{\nu} U(\mathbf{r}_{\nu 1} \cdots \mathbf{r}_{\nu 6}). \quad (3.1)$$

The first sum (i and j) covers all pairs of "atoms" in distinct molecules, and comprises the totality of intermolecular interactions. The second sum (ν) runs over all molecules, and contains the intramolecular potential for each.

The intramolecular force field represented by U contains bond stretching, bond bending, and torsional (dihedral) angle components

$$U = \sum_{i=1}^6 [\frac{1}{2}k_l(l_i - l_0)^2 + \frac{1}{2}k_{\theta}(\theta_i - \theta_0)^2 + u(\phi_i)]. \quad (3.2)$$

Here l_i , θ_i , and ϕ_i are the variable bond lengths, bond-pair angles, and dihedral angles around the cyclic molecule. The torsional potential u has four Fourier components in the manner suggested by Jorgensen,^{15,16}

$$u(\phi) = C_0 + C_1 \cos \phi + C_2 \cos(2\phi) + C_3 \cos(3\phi); \quad (3.3)$$

$\phi=0$ corresponds to the *cis* configuration of the three successive bonds involved.

The intermolecular pair potential v has been given the form used by Stillinger and Weber as a physically and computationally motivated revision of the Lennard-Jones 12,6 interaction^{2,17}

$$v(r) = A\epsilon[(\sigma/r)^{12} - (\sigma/r)^6] \exp[\sigma/(r - d\sigma)]$$

$$(0 < r < d\sigma),$$

$$= 0 \quad (d\sigma \leq r), \quad (3.4)$$

with

$$A = 6.767 \ 44,$$

$$d = 2.464 \ 918 \ 32. \quad (3.5)$$

This function and all its derivatives are continuous at the "cutoff" point $r = d\sigma$, thereby causing no numerical problem either for Newtonian dynamics or for the descent mapping.

Table I specifies values used for the various parameters appearing in U and v . Harmonic stretching and bending force constants were taken from Kollman *et al.*,¹⁸ while Jorgensen's^{15,16} dihedral potentials and intermolecular interactions were used for guidance in selection of the remaining parameters.

The resulting intramolecular potential function U produces the two desired isomers for an isolated cyclohexane molecule. Calculation shows that the twisted-boat U minimum lies 28.647 kJ/mol above that of the chair minimum.

TABLE I. Potential energy parameters for cyclohexane.

Parameters	Value
k_r	2175.68 kJ/mol \AA^2
k_θ	527.18 kJ/mol rad^2
l_0	1.5260 \AA
θ_0	112.40 deg
C_0	8.3973 kJ/mol
C_1	16.786 kJ/mol
C_2	1.1339 kJ/mol
C_3	-26.317 kJ/mol
A	6.767 44
d	2.464 918 32
σ	3.905 \AA
ϵ	0.493 72 kJ/mol

Furthermore, the transition state between them lies 52.689 kJ/mol above the chair minimum. These are each somewhat larger than the previously cited experimental values, but still acceptable for present purposes.

Molecular dynamics simulations have been carried out for a 216 molecule system subject to periodic boundary conditions. Dynamical equations were integrated using the velocity Verlet algorithm with a time step of 0.002 ps.¹⁹ Tem-

perature and pressure respectively were held at 300 K and 1 atm using the method of Berendsen *et al.*²⁰ The cyclohexane molecules were initially placed on a simple cubic lattice, each in the chair conformation. During an ensuing equilibration period, velocities were reassigned from the Boltzmann distribution to enforce proper equilibration among the different modes. Following 273 ps of equilibration during which no isomerization was observed, ten system configurations were saved at 1 ps intervals. Another set of ten configurations was saved, also at 1 ps intervals, beginning 31 ps after occurrence of the last configuration in the first ten. These 20 configurations were used for the pair correlation function and inherent structure studies described in Sec. IV.

In order to generate the mixed isomer system, an all-chair starting state was heated to 2000 K under fixed volume conditions, and maintained in that state for 4 ps. As a result of this harsh treatment, approximately half of the chairs transformed into twisted boats. The velocities of all 1296 atoms were then reassigned from a 300 K Boltzmann distribution, and the system was permitted to equilibrate for 198 ps at 300 K and 1 atm. Following this stage, ten system configurations were saved at 1 ps intervals, then another ten at 1 ps intervals after an intervening lapse of 21 ps. During the entire sampling period, two transitions occurred from twisted-chair to boat form, leaving 104 out of 216 in the twisted-chair state at the end of the simulation.

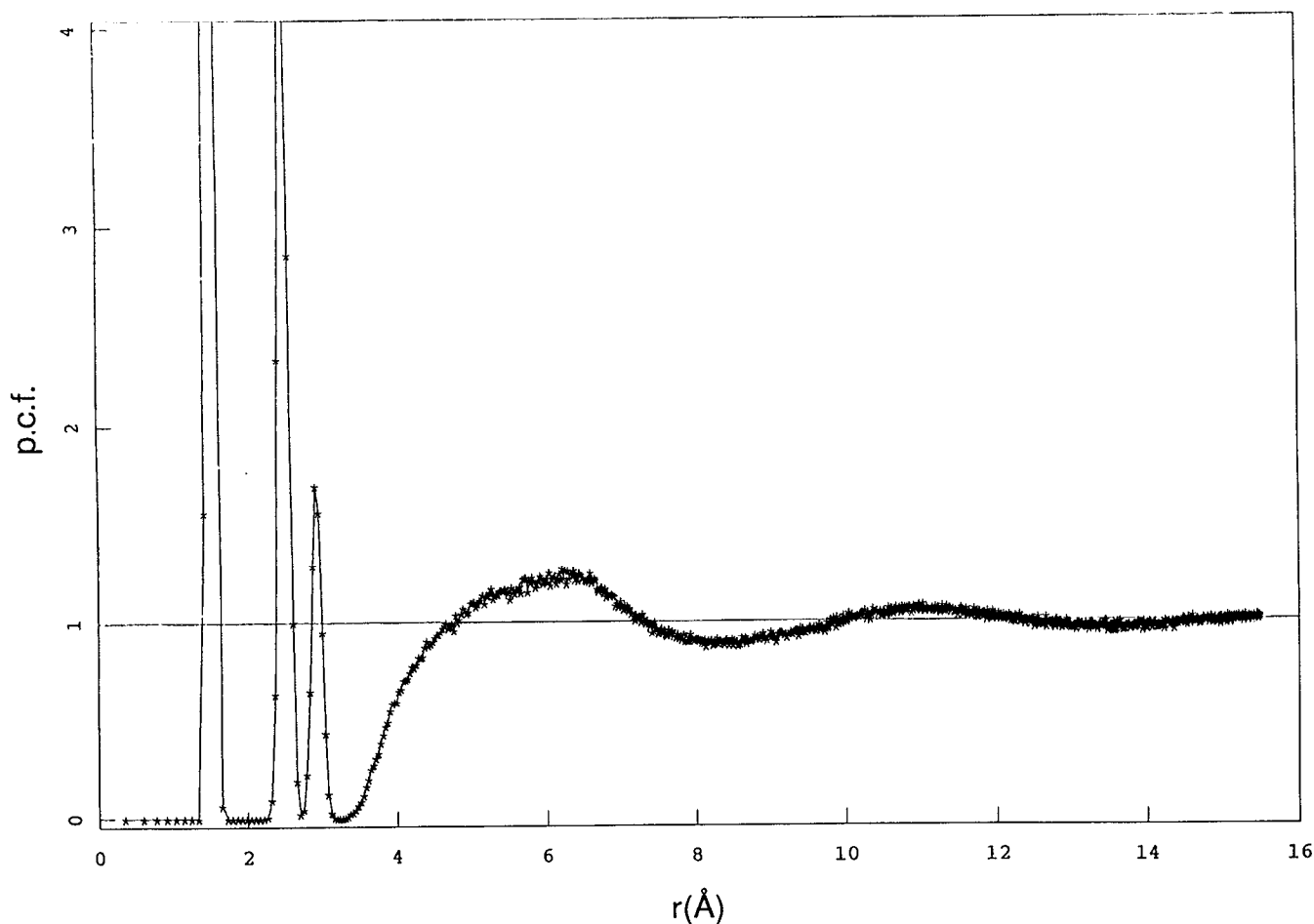


FIG. 3. Pair correlation function for the all-chair cyclohexane liquid at 300 K, 1 atm.

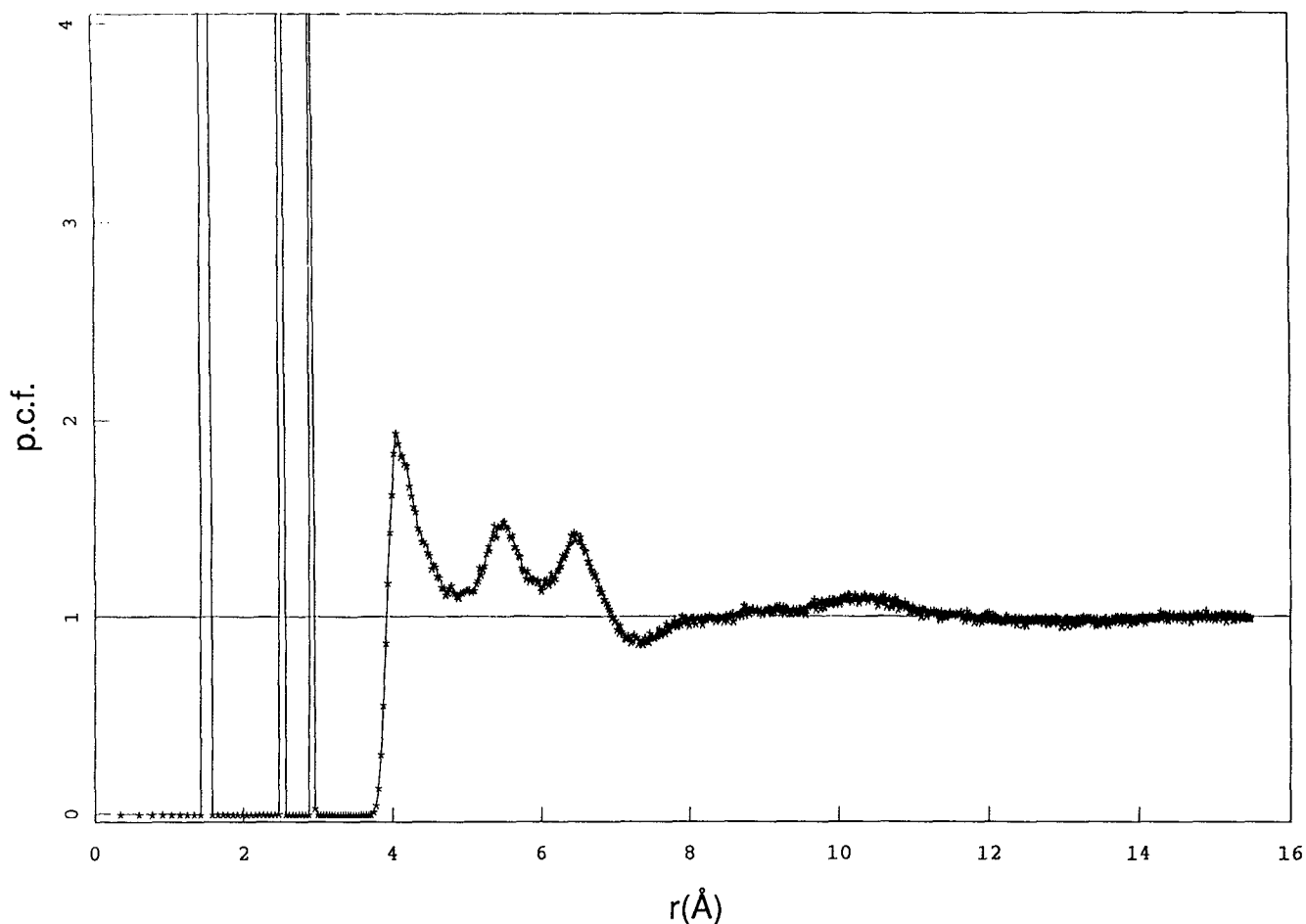


FIG. 4. Pair correlation function for the inherent structures obtained by mapping configurations of the 300 K, 1 atm all-chair liquid onto potential energy minima.

Each of the 40 saved system configurations was mapped onto its corresponding inherent structure by using a combination of direct integration of Eq. (2.1) (for the beginning of the relaxation process), followed by a conjugate gradient algorithm (which finishes the task much more efficiently). Pair correlation functions were evaluated both for premapping and for post-mapping configuration sets. Comparison of results, both for all-chair and for mixed-isomer cases, between the first ten and the later ten configuration subsets revealed no significant systematic differences that would have signalled substantial relaxation processes underway on the molecular dynamics time scale. System volumes were recorded every 0.02 ps during the entire length of each simulation to evaluate the density for the given temperature, pressure, and isomeric composition.

IV. RESULTS

The molecular dynamics calculations indicate that, at most, a small density difference may exist between the two isomeric compositions. The average volumes observed for the two cases lead to densities of 0.7532 and 0.7472 g/cm³ for the all-chair and the mixed-isomer liquids, respectively, at 300 K and 1 atm. This difference is barely significant using a 95% confidence limit computed by the method of Straatsma *et al.*²¹

The density obtained for the all-chair sample is slightly lower than the experimental value 0.774 g/cm³ (298 K). This difference can at least partially be attributed to use of a pair potential v with a finite cutoff on its attractive tail, Eq. (3.4). Restoration of the long-range part of the tail at constant external pressure should produce slight system contraction.

Figures 3–10 reveal the local structure in the two liquids through the pair correlation functions for the “united atoms” comprising the system. Both intramolecular and intermolecular pairs contribute to these functions, which are presented both for premapped and for post-mapped system configurations. Figures 3–6 show the full functions vs distance, while Figs. 7–10 focus on expanded views of intramolecular contributions.

In both the all-chair (Figs. 3 and 4) and the mixed-isomer (Figs. 5 and 6) cases the mapping onto inherent structures significantly sharpens and elaborates the correlation features, whether intramolecular or intermolecular. One obvious effect is that the broad intermolecular first maximum occurring near 6 Å in both Figs. 3 and 5, clearly splits into three components, Figs. 4 and 6, upon reduction to the respective inherent structures. It is also obvious that the mapping to minima substantially sharpens the intramolecular correlations present in the figures below about 3.3 Å;

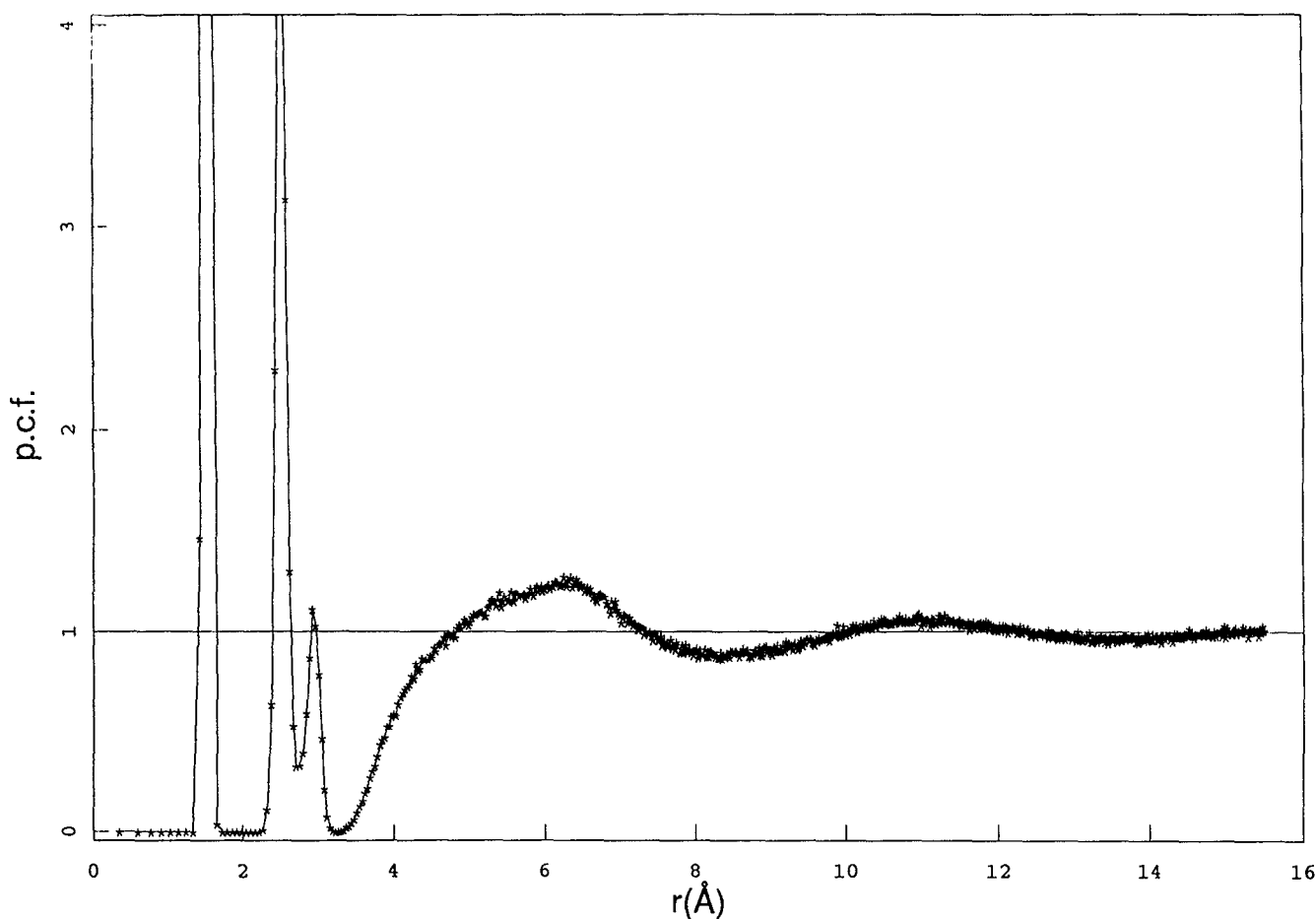


FIG. 5. Pair correlation function for the mixed-isomer cyclohexane liquid at 300 K, 1 atm.

in particular three intramolecular peaks become five peaks for the mixed isomer case. Any residual post-mapping width displayed by intramolecular peaks arises from the inhomogeneous distribution of stresses present in the amorphous inherent structures for the system.

Careful comparison of Figs. 3 and 4, and of Figs. 5 and 6, shows an apparent inward shift of intermolecular correlation features resulting from the mapping. Doubtless it stems mostly from removal of very anharmonic vibrations and librations, thereby permitting changes in relative mean positioning of neighboring molecules.

A surprising observation is the remarkable similarity of the intermolecular correlations ($r > 3.3 \text{ \AA}$) for both samples. This is true even after invoking the remarkable structure enhancing influence of the mapping operation. Within our statistical uncertainty, the intermolecular short-range order appears to be unaffected by isomerization of the cyclohexane molecules.

Figures 7–10 show horizontally magnified details of those portions of the intramolecular correlations depending on second and third neighbors around the cyclohexane rings. Clearly almost all of the room-temperature broadening arises from vibrational motion that is removed entirely by mapping. Fluctuating intermolecular stresses play a rela-

tively minor role.

In an unperturbed chair-form isomer, Fig. 1, all united atoms are equivalent, so three intramolecular pair distances are distinguishable. The unperturbed twisted-chair isomer, Fig. 2, possesses two types of united atoms, and six pair distances that in principle are distinguishable. Under present circumstances, though, only two additional intramolecular peaks arise in the correlation functions when twisted-chair isomers are added to the medium, since such small distance differences would be involved for full discrimination. Nevertheless, these two new components clearly indicate the presence of the higher-energy isomers after system configurations have been mapped onto inherent structures. In fact, the shoulder present in the expanded view of Fig. 10(a) represents a partial resolution of one of these two twisted-chair components.

Figures 11–14 present distributions of intramolecular potential energies U extracted from the sets of 20 system configurations before and after mapping. These results parallel those for intramolecular distances, not surprisingly. Before mapping, the all-chair and the mixture cases appear, respectively, as unimodal (Fig. 11) and as bimodal (Fig. 13) broad distributions. After mapping, these collapse to extremely narrow components (Figs. 12 and 14).

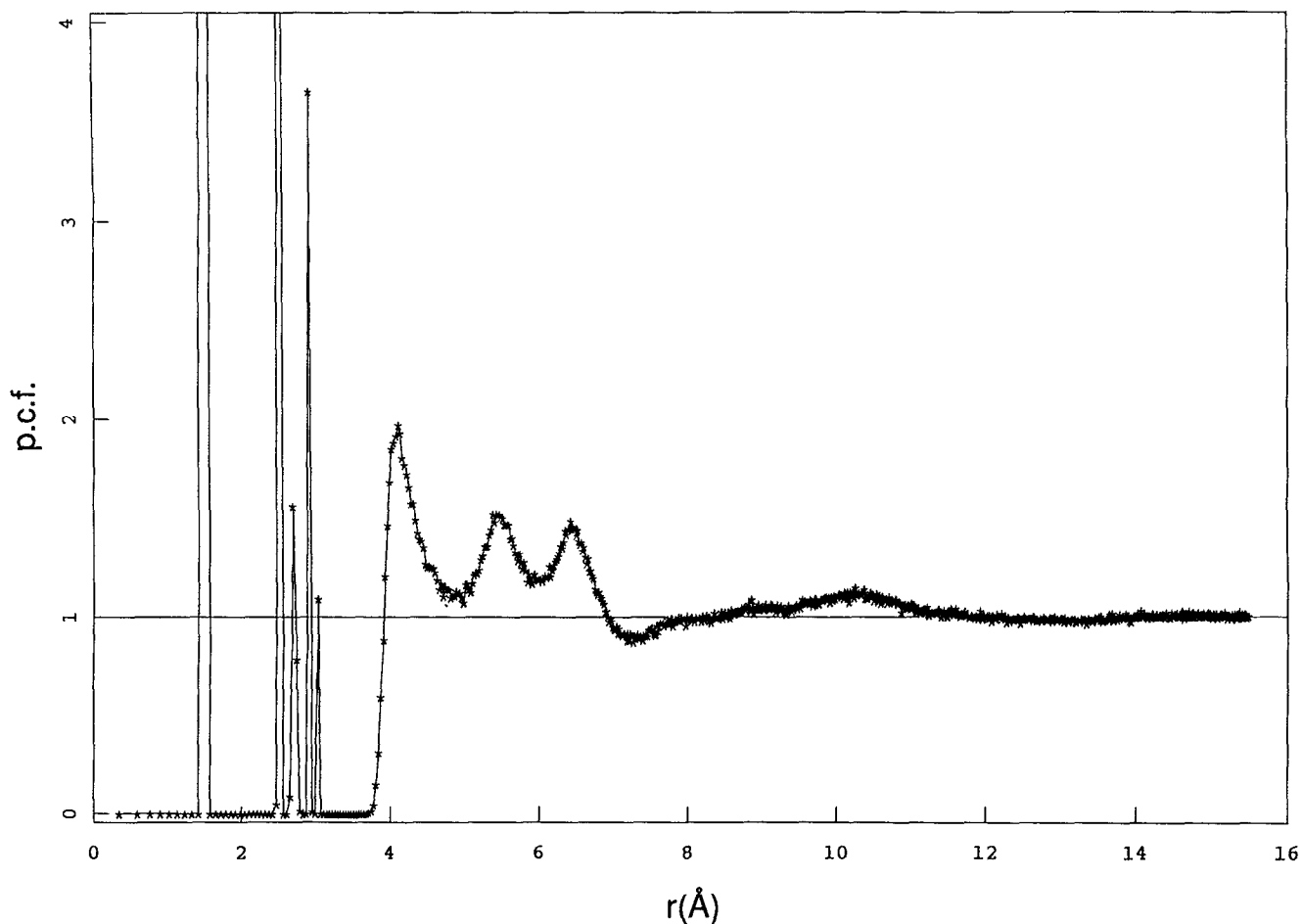


FIG. 6. Inherent structure pair correlation function obtained by mapping configurations of the 300 K, 1 atm mixed-isomer liquid onto potential energy minima.

V. DISCUSSION

The calculations reported above demonstrate the capacity of the inherent structure approach to resolve ambiguities about which isomeric species are present in condensed phase systems. The premapped pair correlation functions shown in Figs. 3 and 5 contain very similar-appearing intramolecular portions ($r < 3.3$ Å), whose resolution into separate chair and twisted-boat components would be difficult at best. The correlation structure is remarkably enhanced by mapping onto inherent structures, and the contributions of the two types of isomers to intramolecular correlation is clearly distinguishable, as comparison of Figs. 4 and 6 readily demonstrates. This situation is analogous to that encountered in the molecular dynamics simulation of chemically reactive systems, where the unambiguous identification of distinct chemical species is only possible after mapping onto inherent structures. Examples of this latter phenomenon that have

been investigated in detail include liquid sulfur,⁸⁻¹⁰ compressed fluorine gas,¹¹ and the silicon fluorides.^{12,13}

Two predictions emerge from our study concerning solid amorphous deposits of cyclohexane that could be formed from the vapor on very cold substrates. The short-range order in such deposits should correspond closely to that of the inherent structures reported here. In particular, we predict the occurrence of a triple-peaked form of close intermolecular pairs as shown in Figs. 4 and 6, followed by a broad and barely distinguishable pair correlation maximum centered near 10.5 Å. These intermolecular pair correlation characteristics furthermore should be virtually invariant to the presence of twisted-boat isomers, which presumably could be incorporated stably into cold deposits by rapid condensation from very hot vapor, or by radiation excitation *in situ*. We urge that such experiments be undertaken to form the deposits, and to determine their short-range order by diffraction.

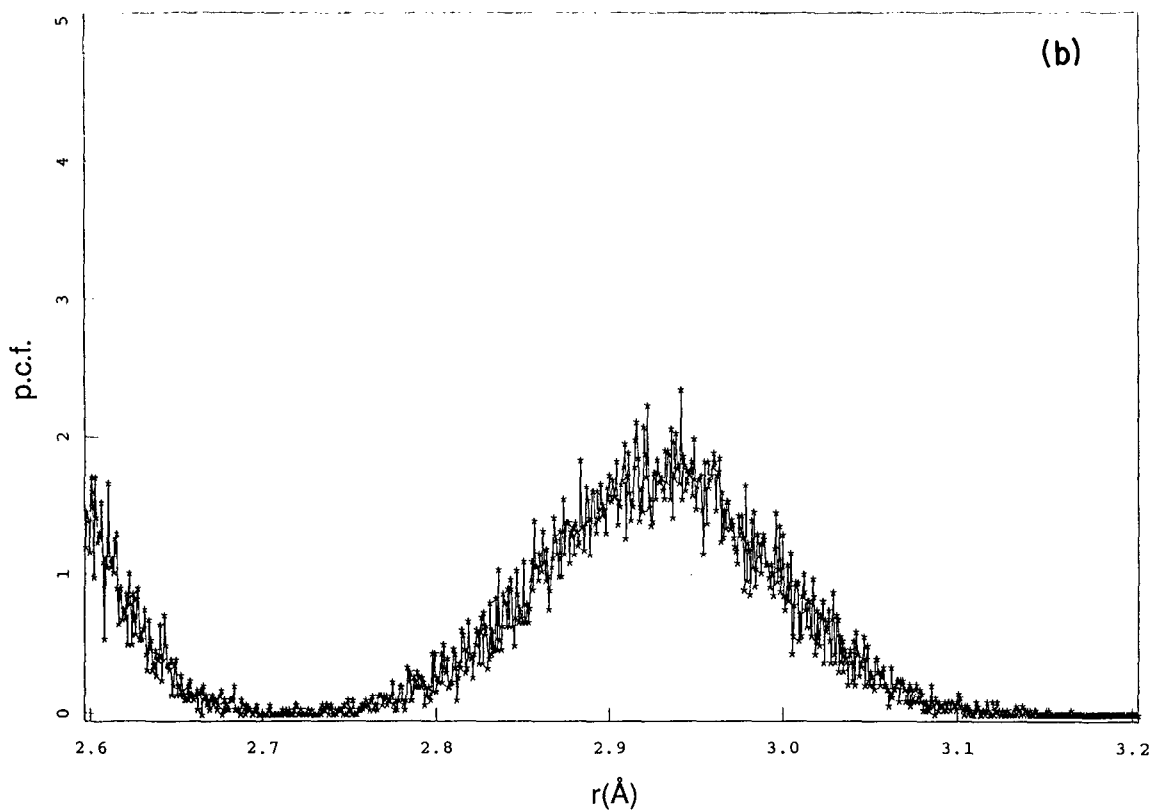
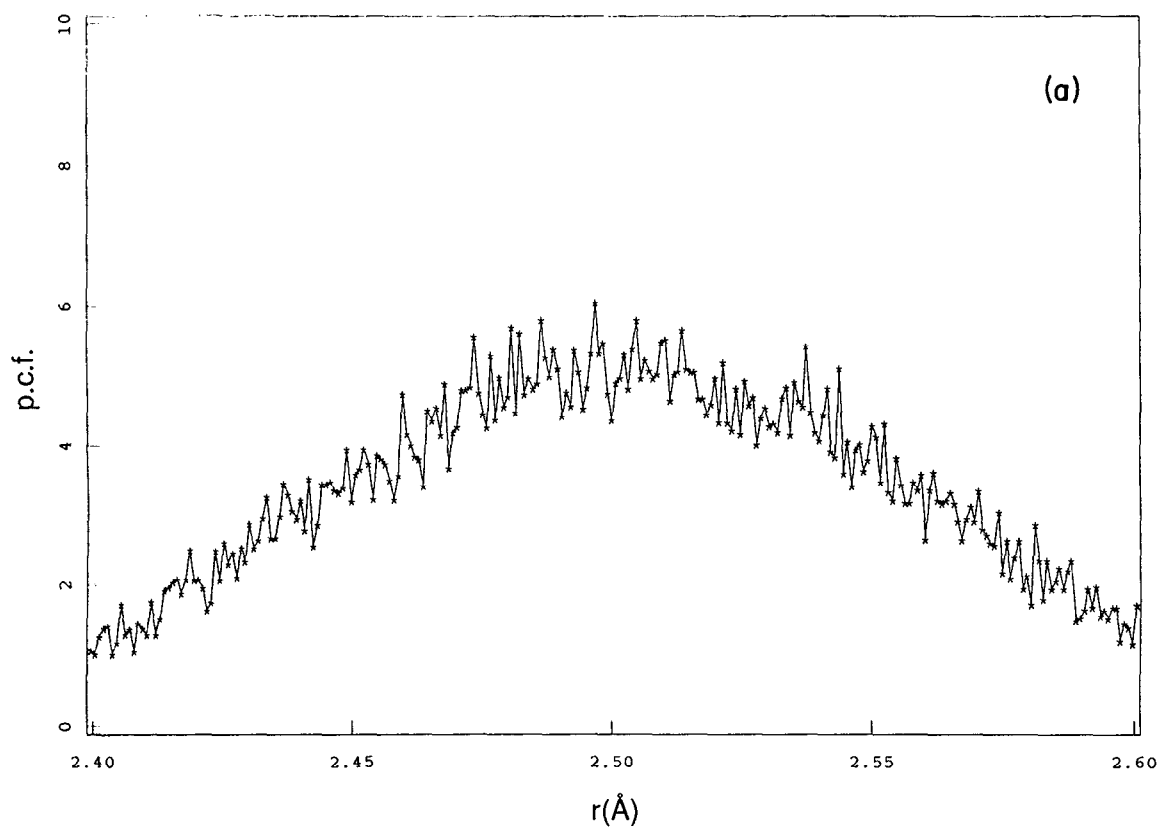


FIG. 7. Expanded view of the (a) second, and (b) third neighbor portions of premapping intramolecular pair correlations. These refer to the all-chair liquid.

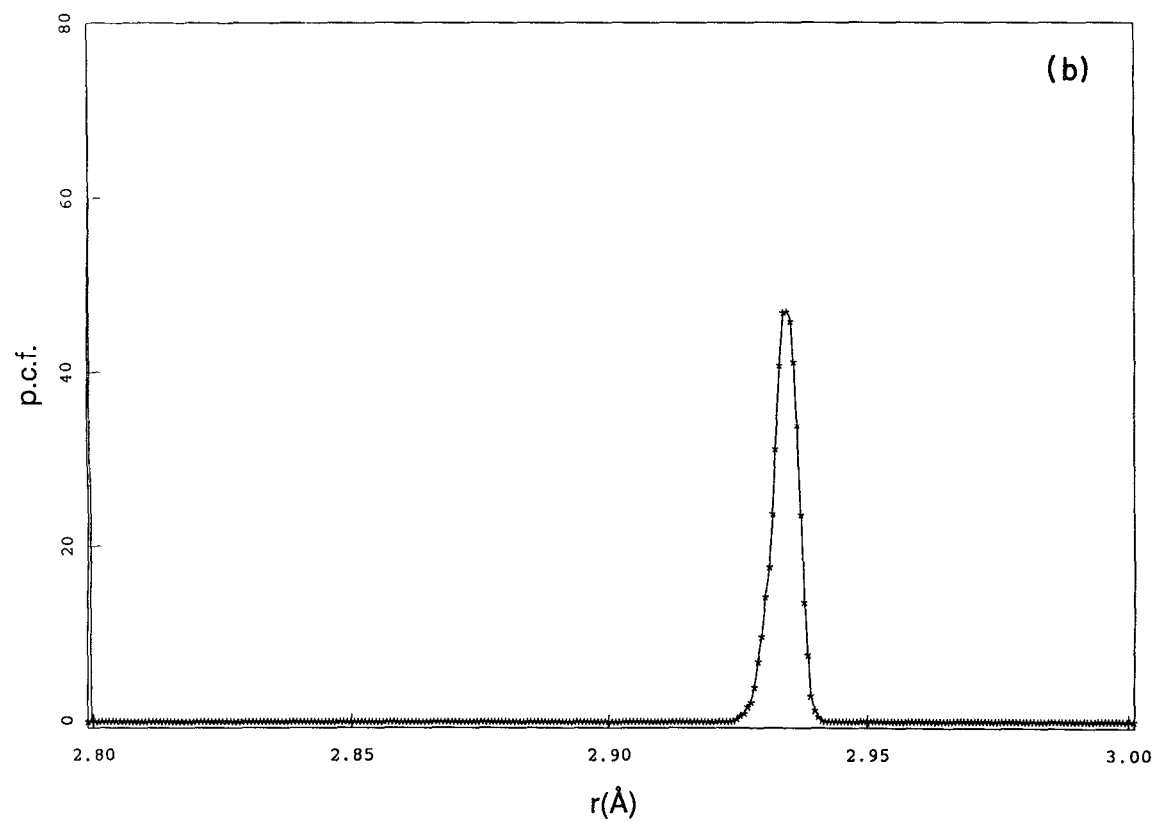
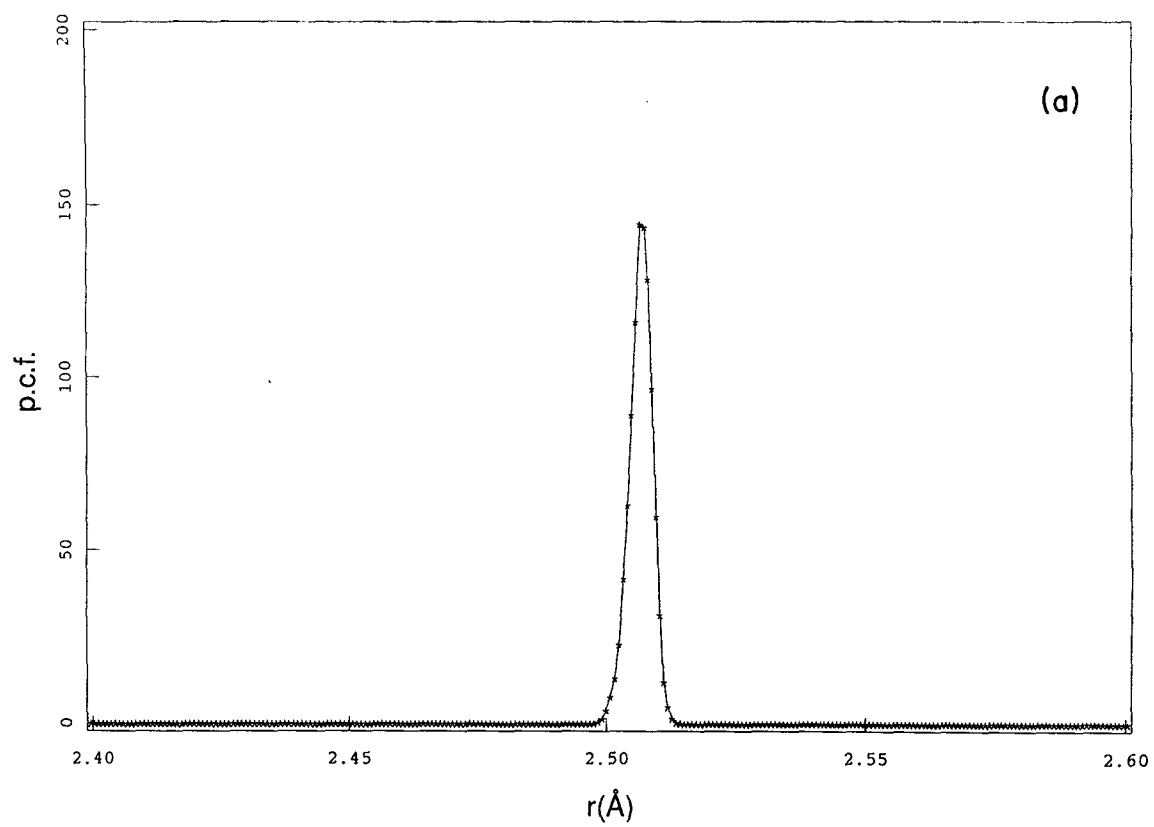


FIG. 8. Expanded view of the intramolecular pair correlation regions of Fig. 7(a) and (b) following mapping onto inherent structures.

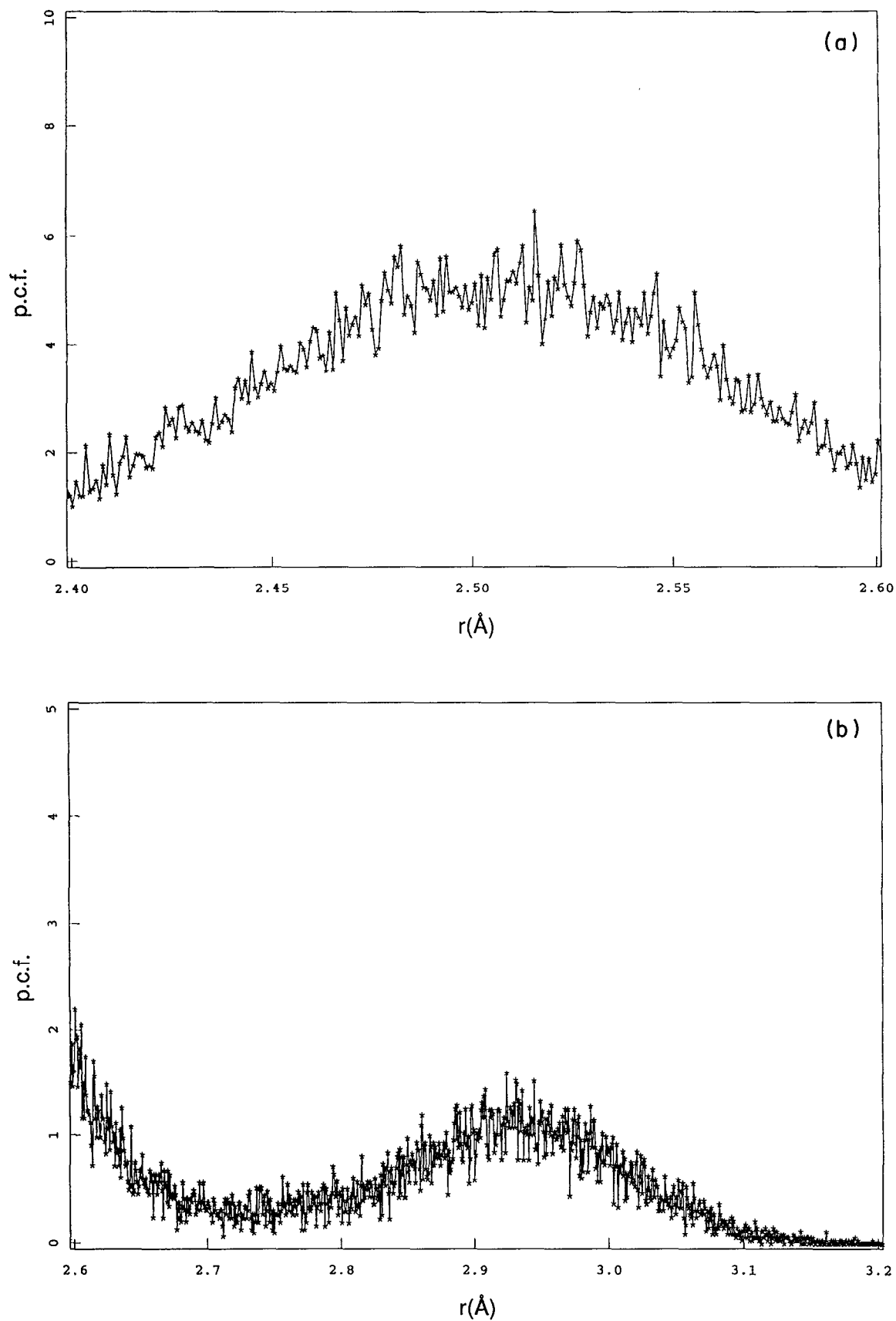


FIG. 9. Expanded view of the (a) second, and (b) third neighbor portions of premapping intramolecular pair correlations for the mixed-isomer liquid.

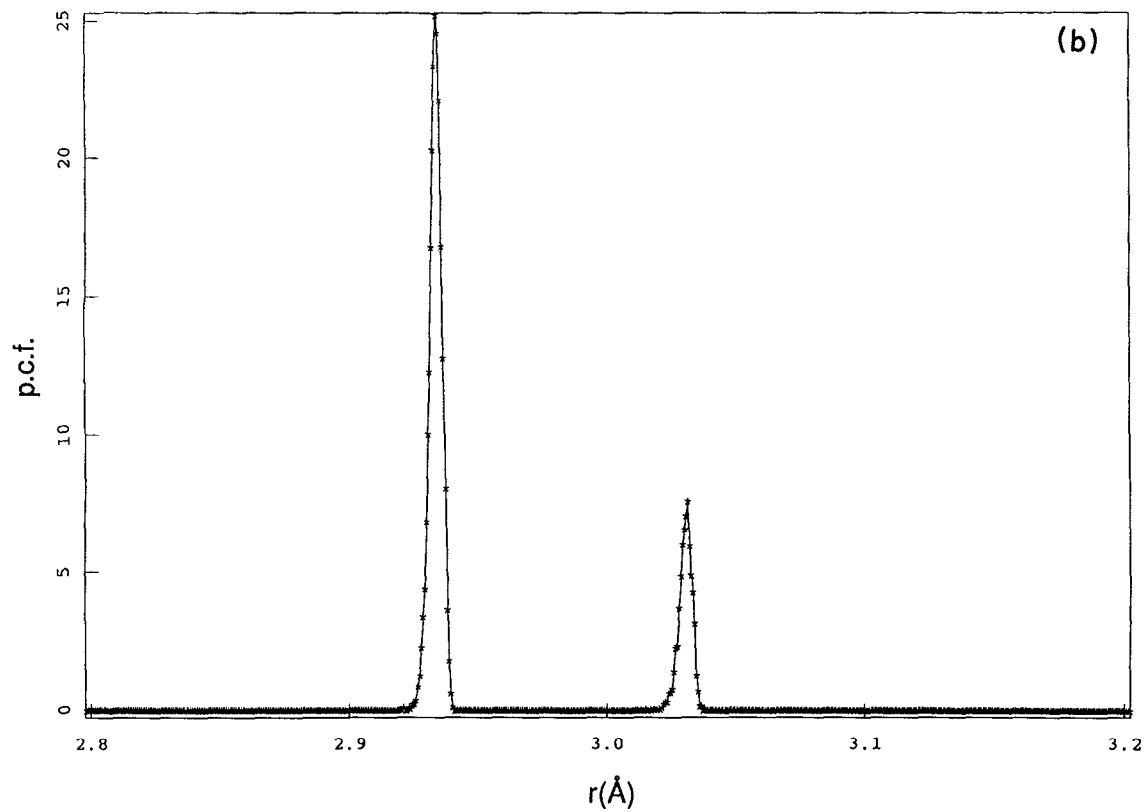
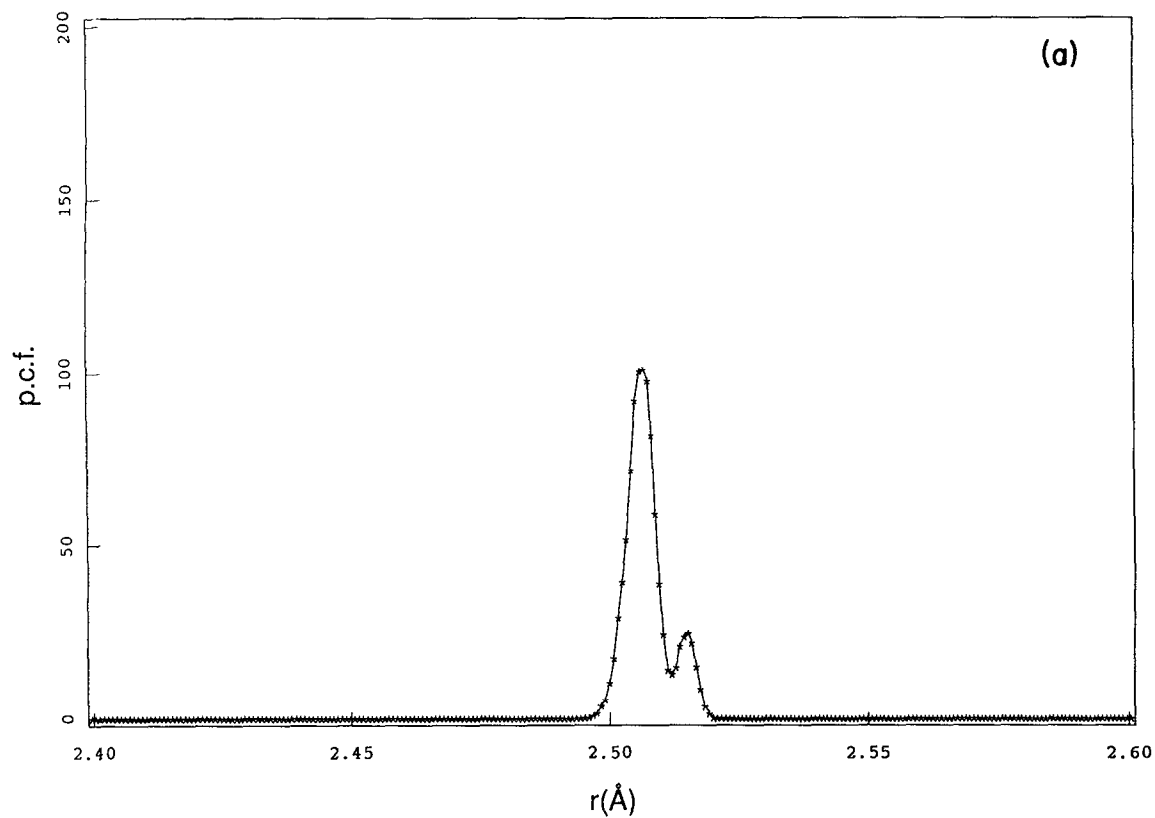


FIG. 10. Expanded view of the intramolecular pair correlation regions of Figs. 9(a) and (b) following mapping onto inherent structures.

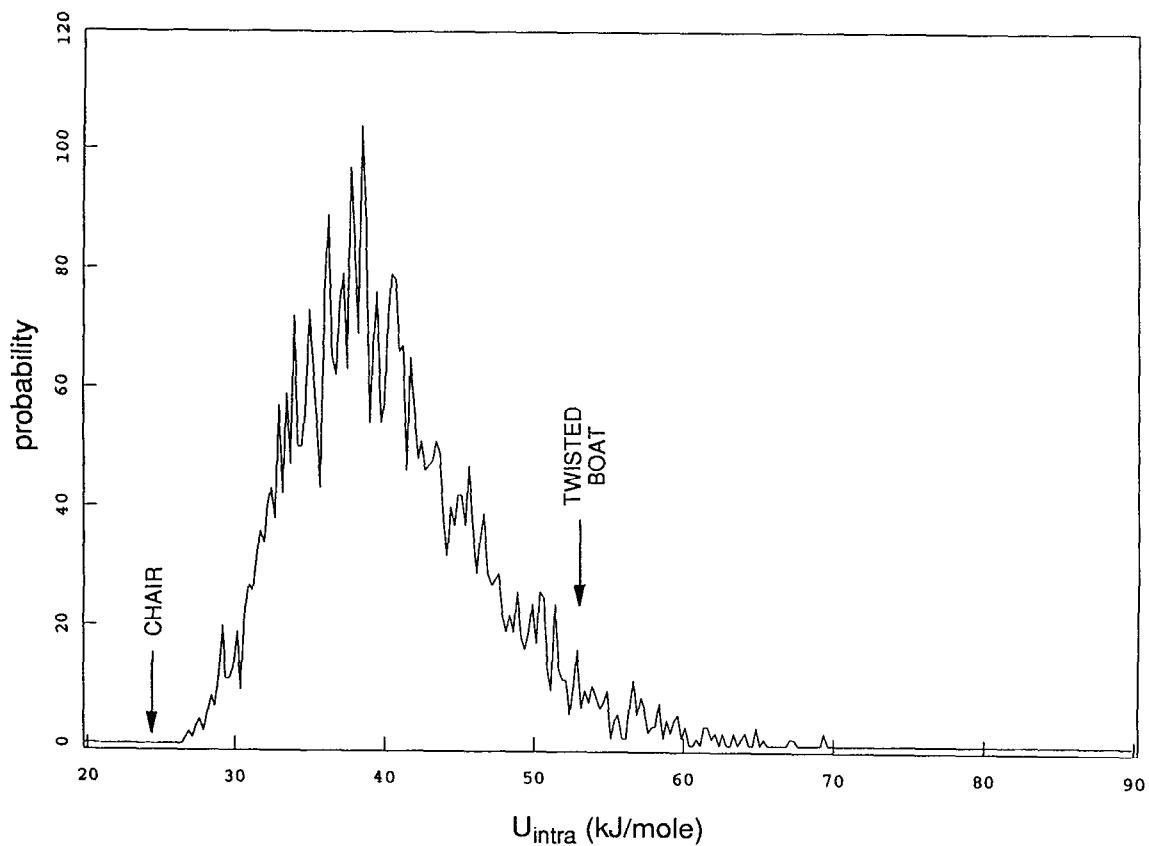


FIG. 11. Distribution of intramolecular energies in the all-chair liquid at 300 K, 1 atm. The arrows show the energies of the static unperturbed isomers.

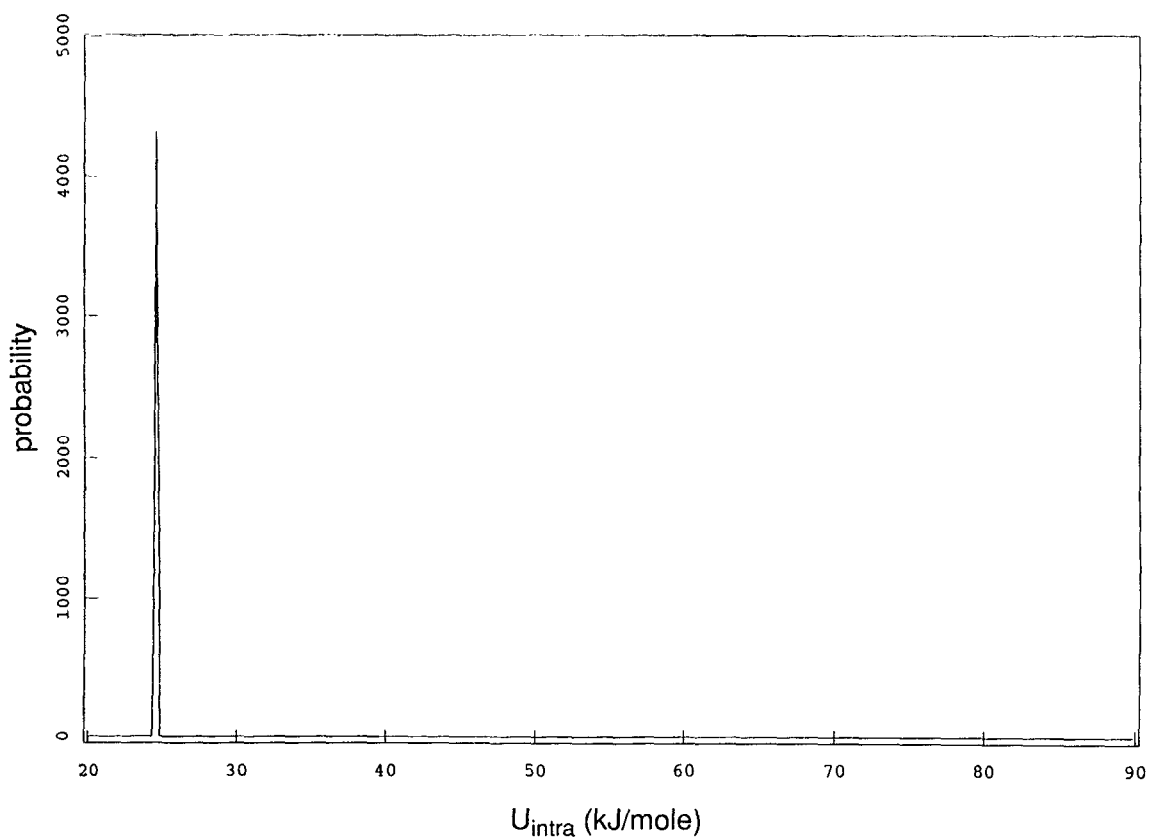


FIG. 12. Distribution of intramolecular energies obtained after mapping configurations of the all-chair liquid onto potential energy minima (inherent structures).

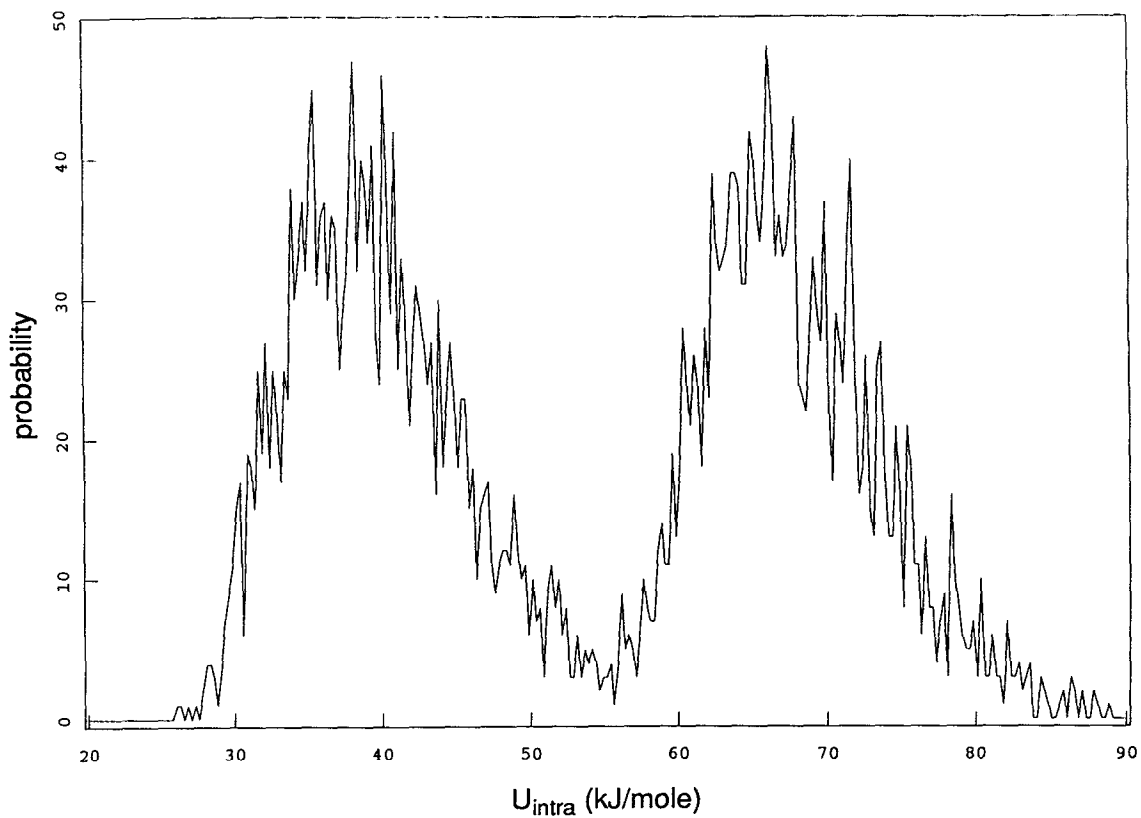


FIG. 13. Distribution of intramolecular energies in the mixed-isomer liquid at 300 K, 1 atm.

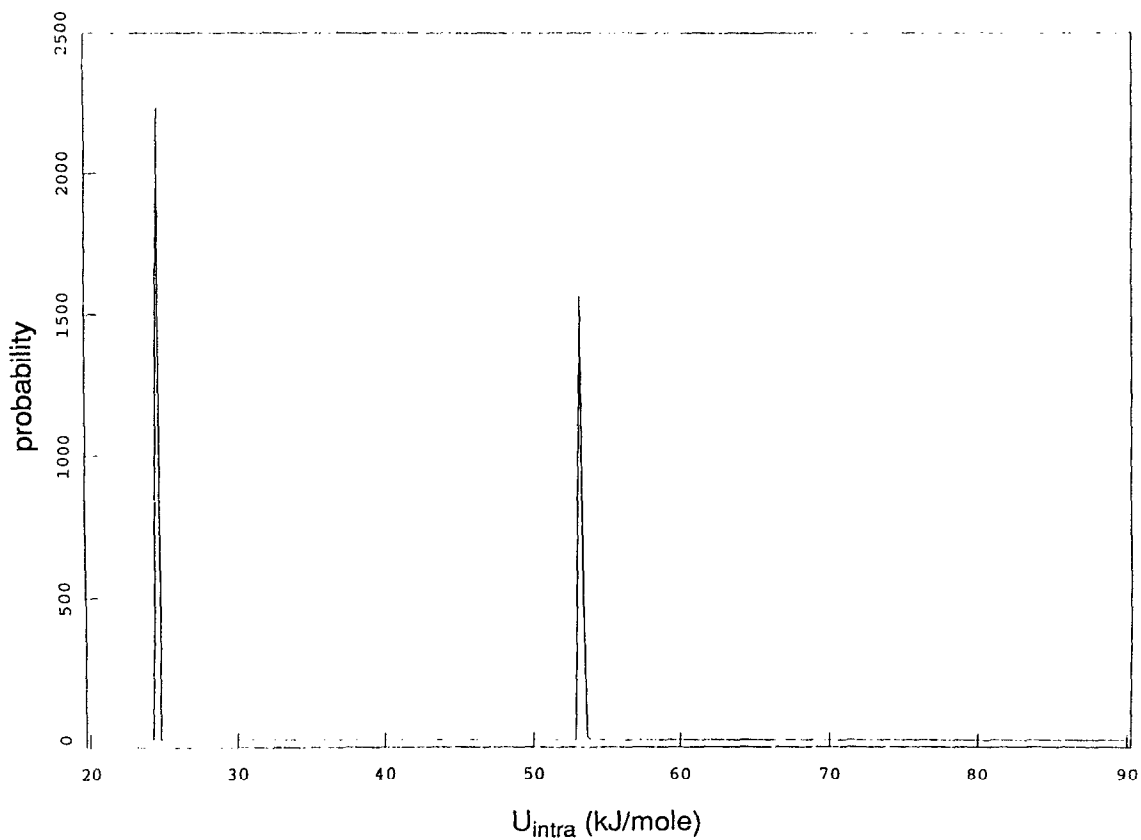


FIG. 14. Distribution of intramolecular energies obtained after mapping configurations of the mixed-isomer liquid onto potential energy minima.

Finally, the present study constitutes a challenge to non-simulational theory of molecular fluids. In particular, it would be illuminating to apply the popular RISM approach²² to see if its pair correlation function conclusions accord with those reached herein.

- ¹ F. H. Stillinger and T. A. Weber, *Phys. Rev. A* **25**, 978 (1982).
- ² F. H. Stillinger and T. A. Weber, *Phys. Rev. A* **28**, 2408 (1983).
- ³ F. H. Stillinger and T. A. Weber, *J. Phys. Chem.* **87**, 2833 (1983).
- ⁴ F. H. Stillinger and T. A. Weber, *Science* **228**, 983 (1984).
- ⁵ F. H. Stillinger and T. A. Weber, *J. Chem. Phys.* **80**, 4434 (1984).
- ⁶ M. Squillacote, R. S. Sheridan, O. L. Chapman, and F. A. L. Anet, *J. Am. Chem. Soc.* **97**, 3244 (1975).
- ⁷ (a) D. L. Hasha, T. Eguchi, and J. Jonas, *J. Am. Chem. Soc.* **104**, 2290 (1982); (b) F. A. L. Anet and R. Anet, in *Dynamic Nuclear Magnetic Resonance Spectroscopy*, edited by L. M. Jackman and F. A. Cotton (Academic, New York, 1975), p. 543; (c) F. A. L. Anet and A. U. R. Bourn, *J. Am. Chem. Soc.* **89**, 760 (1967).
- ⁸ F. H. Stillinger, T. A. Weber, and R. A. LaViolette, *J. Chem. Phys.* **85**, 6460 (1986).
- ⁹ F. H. Stillinger, in *Statphys 16*, edited by H. E. Stanley (North Holland, Amsterdam, 1986), pp. 142–149.
- ¹⁰ F. H. Stillinger and T. A. Weber, *J. Phys. Chem.* **91**, 4899 (1987).
- ¹¹ F. H. Stillinger and T. A. Weber, *J. Chem. Phys.* **88**, 5123 (1988).
- ¹² F. H. Stillinger and T. A. Weber, *Phys. Rev. Lett.* **62**, 2144 (1989).
- ¹³ T. A. Weber and F. H. Stillinger, *J. Chem. Phys.* **95**, 3614 (1991).
- ¹⁴ F. H. Stillinger, *Phys. Rev. B* **41**, 2409 (1990).
- ¹⁵ W. L. Jorgensen, J. D. Madura, and C. J. Swenson, *J. Am. Chem. Soc.* **106**, 6638 (1984).
- ¹⁶ W. L. Jorgensen and J. Tirado-Rives, *J. Am. Chem. Soc.* **110**, 1657 (1988).
- ¹⁷ R. A. LaViolette and F. H. Stillinger, *J. Chem. Phys.* **83**, 4079 (1985).
- ¹⁸ S. J. Weiner, P. A. Kollman, D. A. Case, U. C. Singh, C. Ghio, G. Alagona, S. Profeta, and P. Weiner, *J. Am. Chem. Soc.* **106**, 765 (1984).
- ¹⁹ H. C. Andersen, *J. Comp. Phys.* **52**, 24 (1983).
- ²⁰ H. J. C. Berendsen, J. P. M. Postma, W. F. van Gunsteren, A. DiNola, and J. R. Haak, *J. Chem. Phys.* **81**, 3684 (1984).
- ²¹ T. P. Straatsma, H. J. C. Berendsen, and A. J. Stam, *Mol. Phys.* **57**, 89 (1986).
- ²² C. S. Hsu, L. R. Pratt, and D. Chandler, *J. Chem. Phys.* **68**, 4213 (1978), and references therein.