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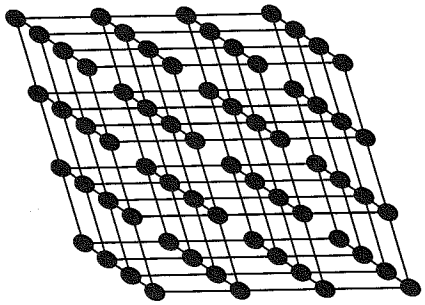
Crystal Growth of Organic Materials



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Proceedings of a conference sponsored
by E.I. du Pont de Nemours and Company,
Biosym/Molecular Simulations,
and American Institute of Chemical Engineers
Washington, D.C.,
August 27–31, 1995

American Chemical Society, Washington, DC

Library of Congress Cataloging-in-Publication Data

Crystal growth of organic materials / edited by Allan S. Myerson, Daniel A. Green, Paul Meenan.

p. cm.—(Conference proceedings series, ISSN 1054–7487)

"Proceedings of a conference sponsored by E.I. du Pont de Nemours and Company, Biosym/Molecular Simulations, and American Institute of Chemical Engineers, Washington, D.C., August 27–31, 1995."

Papers from the Third International Workshop on Crystal Growth of Organic Materials.

Includes bibliographical references and index.

ISBN 0–8412–3382–9 (alk. paper)

1. Crystallization—Industrial applications—Congresses. 2. Chemistry, Organic—Industrial applications—Congresses.

I. Myerson, Allan S., 1952– . II. Green, Daniel A., 1958– . III. Meenan, Paul, 1965– . IV. E.I. du Pont de Nemours and Company. V. Biosym/Molecular Simulations Inc. VI. American Institute of Chemical Engineers. VII. International Workshop on Crystal Growth of Organic Materials (3rd: 1995: Washington, D.C.) VIII. Series: Conference proceedings series (American Chemical Society)

TP156.C57C79 1996
661′.8—dc20 96–1348
CIP

The Application Of Computational Chemistry to the Study Of Molecular Materials.

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An understanding of the specific arrangements of molecules in the solid state allows the chemist to manipulate the solid state to optimise the performance characteristic of interest. In this paper the application of molecular modelling and computational chemistry techniques to the study of molecular materials will be described including lattice energy calculations, crystal shape prediction property estimation methods and crystal structure prediction/determination. The potential and limitations of these methods will be discussed.

Introduction

An understanding of the specific arrangements adopted by molecules within the crystal lattice allows the solid state chemist to manipulate the crystal chemistry to optimise the performance characteristic of interest.

Given the importance of crystal engineering and polymorph control to the development and production of a vast range of speciality chemicals (i.e. pharmaceuticals, agrochemicals, pigments, dyes, opto-electronic materials and explosives) it is not surprising that many techniques are applied to improve our understanding of the solid state structure of such materials. Over recent years molecular modelling and computational chemistry have played and increasingly important role in this field.

The solid state arrangement(s) adopted by a molecules depends on the subtle balance of intermolecular interactions that it can achieve for a given conformation in a particular packing arrangement. Crystallisation and the properties of the solid state are dependent on a process which is essentially molecular recognition on a grand scale. Polymorphism and changes in properties are due to the recognition of different balances of these subtle interactions. In this paper the use of molecular modelling to establish the link between molecular structure, intermolecular interactions packing motifs and solid state property will be illustrated.

Molecular Modelling

Molecular modelling and computational chemistry methods operate on three levels. Firstly molecular modelling is almost unique in it's ability in allowing the examination of the detailed, complex and often elegant arrangements of molecules, proteins, fibres, polymers, surfaces and solid state structures. Secondly in conjunction with computational chemistry molecular modelling permits the determination of structure activity relationships (SAR's) linking calculated properties and hence molecular structure to performance characteristics. Ultimately it enables (based in these SAR's) the design of novel molecular/solid state structures with improved properties and performance characteristics.

The Crystal Chemistry Of Molecular Materials

The structures and crystal chemistry of molecular materials are often classified into different categories according to the type of intermolecular forces present. These include;

* simple Van der Waals attractive interactions,
* classical hydrogen bonding (Taylor, 1982),
* electrostatic interactions,
* C-H:::::O non classical hydrogen bonding,
* short directional contacts (Desiraju, 1989).

Molecules can essentially be regarded as impenetrable systems whose shape and volume characteristics are governed by the molecular conformation and the radii of their constituent atoms. The general uneven, awkward shape of molecular structures tends to result in unequal unit cell parameters being adopted during crystallisation. The vast majority of the structures

1054–7487/96/0002$12.00/0

reported prefer the triclinic, monoclinic and orthorhombic crystal systems.

A useful parameter for judging the efficiency of a molecule for using space in a given solid state arrangement is the packing co-efficient (PC). This model assumes that the molecules within the crystal will attempt to pack in a manner such as to minimise the amount of unoccupied space (Kitaigorodskii, 1973).

In general there is a rough correlation between higher PC values and increasing size of large flat aromatic molecules i.e perylene (0.8). Once even slight deviations from planarity are introduced the effective packing ability falls. For benzophenone, an aromatic ketone ($Ph_2C=O$) the phenyl groups are twisted to 54° with respect to each other and the PC falls to 0.64. One of the most interesting features of such a model is the low PC for hydrogen bonded systems such as urea (0.65) and benzoic acid (0.62). This rather surprising feature is due to the rather open architecture of hydrogen bonded structures which is the result of a need to adopt particular arrangements to maximise the hydrogen bonded network (Etter, 1991).

In general it is probably safe to suggest that in the majority of cases with molecular materials it is the desire to pack efficiently is the single biggest driving force towards selected structural arrangements. The notable exceptions will be in cases where the need to form complex hydrogen bonding networks will override this need. Weaker interactions such as special hydrogen bonds and polar interactions are probably not primary movers in the arrangements adopted but will tend to be optimised within a given efficient arrangement.

Lattice Energy Calculations

In order to understand the principles which govern the wide variety of solid state properties and structures of organic materials it is important to describe both the energy and nature of interactions in specific orientations and directions. As a result of the pioneering work of Williams (1966) and Kitaigordskii (1968) in the development of atom-atom potentials it is now possible to interpret packing effects in organic crystals in terms of interaction energies. The basic assumption of the atom-atom method is that the interaction between two molecules can be considered to simply consist of the sum of the interactions between the constituent atom pairs.

The lattice energy E_{latt} (often referred to as the crystal binding or cohesive energy), can for molecular materials be calculated by summing all the interactions between a central molecule and all the surrounding molecules. If there are n atoms in the central molecule and n' atoms in each of the N surrounding molecules then lattice energy can be calculated by Equation (1).

$$E_{latt} = 1/2 \sum_{k=1}^{N} \sum_{i=1}^{n} \sum_{j=1}^{n'} V_{kij} \quad \text{---------(1)}$$

V_{kij} is the interaction between atom i in the central molecule and atom j in the k'th surrounding molecule. Each atom-atom interaction pair consists of a Van der Waals attractive and repulsive interaction, an electrostatic interaction and in some special cases a hydrogen bonding potential. Figure 1 shows the profiles of the calculated lattice energy as a function of summation limit for α-glycine, anthracene, ß-succinic acid and urea. These plots show the same general trend, on increasing the summation limit there is an initial increase in the lattice energy is recorded. This is followed by the reaching of a plateau region beyond 20Å. Further increase in the summation limit has no effect on the calculated lattice energy.

The validity of the potentials can to some extent be tested by comparing the theoretical values against the experimental sublimation enthalpy. Table 1 contains a selection of calculated lattice energies and experimental sublimation enthalpies. Figure 2 shows a plot of calculated against experimental lattice energies for a range of around eighty compounds. The molecular classes reported include a wide range of molecular materials. The excellent agreement between theory and experiment is clear, the mean error is 1.5 kcal/mol and the maximum error 3.5 kcal/mol. The average difference between calculated and experimental less than 6%.

Intermolecular Interactions

A particular advantage of the calculated lattice energy is that it can be broken down into the specific interactions along particular directions and further partitioned into the constituent atom-atom contributions.

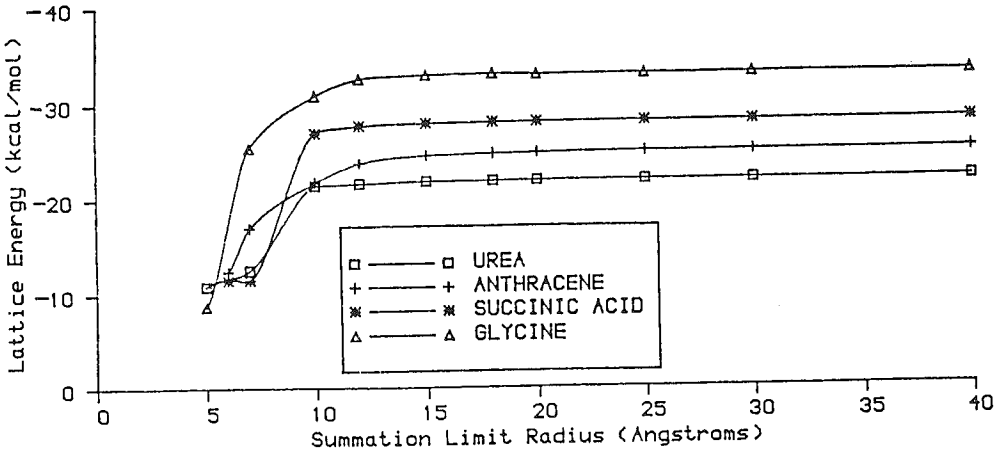

Figure 1 The calculated lattice energy as a function of summation limit for anthracene, urea, succinic acid and glycine

Table 1 Calculated and 'experimental' lattice energiess for a range of molecular materials. This is a subset of the data presented in Figure 2.

Material	Lattice Energies (kcal/mol) Calculated	Experimental
n-Octadecane	-35.2	-37.8
Biphenyl	-21.6	-20.7
Napthalene	-19.4	-18.6
Anthracene	-24.9	-26.2
Perylene	-32.5	-31.0
Benzophenone	-24.5	-23.9
Trinitrotoluene	-25.1	-24.4
Glycine	-33.0	-33.8
L-alanine	-33.3	-34.2
Benzoic acid	-20.4	-23.0
Urea	-22.7	-22.2
ß-succinic acid	-30.8	-30.1

As a result it is possible to build up an understanding of the interactions which contribute to particular packing motifs. The study of the strength and geometry of intermolecular interactions remains an area of active research as it is a key element in molecular solid state chemistry (as described in the elegant work by Etter, 1991), in the design of molecular aggregates and in the understanding and construction of molecular recognition complexes for biologically interesting substrates (Chang and Hamilton, 1988).

Urea (see Fig 3) has a three dimensional arrangement of hydrogen bonds where each urea molecule is surrounded by six other urea molecules. This cluster is responsible for 85% of the total lattice energy. The important intermolecular interactions are given in Table 2.

The calculated intermolecular interactions, in particular the weaker ones, can be further examined to determine their relative importance, geometry and strength by using the vast amount of experimental data available in the Cambridge Crystallographic Database.

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