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FERMICONDENSATION - AN ALMOST IDEAL GLASS TRANSITION

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ABSTRACT

A fermisystem in a thermodynamic density of states evaporates into a classical gas at a finite temperature. The converse process, "fermicondensation", is shown to be close to an ideal glass transition (a transition to a state of zero entropy at a positive temperature). The fermicondensation phenomenon has a number of properties in common with Derrida's random energy model. The present study of the two models weakens the Adam-Gibbs hypothesis concerning a diverging average relaxation time at the ideal glass transition.

1. INTRODUCTION

Most liquids are able to form glasses when cooled sufficiently fast to avoid crystallization [1,2]. Examples of glass forming liquids include polymeric liquids, ionic liquids, molten salts or metals, simple organic liquids, and the various oxides forming ordinary glass. The glass transition is not an ordinary phase transition, but a kinetic phenomenon. The transition is not sharp and its characteristic temperature, T_g , depends somewhat on the cooling rate. There are, however, speculations that the experimental glass transition is a manifestation of an underlying genuine second order phase transition to a state of zero entropy, an "ideal glass transition". This idea was proposed by Gibbs and DiMarzio in 1958 [3]. It resolves the socalled Kauzmann paradox [4,5], i. e. , the fact that the excess entropy of the supercooled liquid upon cooling extrapolates to zero at a positive temperature T_o . The excess entropy is the entropy of the liquid in excess of the purely vibrational contribution (estimated by the entropy of the crystal at the same temperature). This quantity represents the configurational entropy of the liquid and must be positive. Thus, either the extrapolation is incorrect or there is a phase transition at T_o to a state of zero configurational entropy, an "ideal glass". The real glass transition intervenes before T_o is reached, though, and the existence of an underlying ideal glass transition remains a conjecture.

Henceforth attention is focussed on the thermodynamics of the configurational degrees of freedom only; the vibrational degrees of freedom are ignored since they undergo little change at the

glass transition. Any thermodynamic system is characterized by the entropy as function of energy, S(E) [6]. The temperature is defined by

$$\frac{1}{T} = \frac{\partial S}{\partial E} \quad . \tag{1}$$

The requirements of a positive temperature and of a non-negative specific heat lead to

$$\frac{\partial S}{\partial E} > 0 \quad , \quad \frac{\partial^2 S}{\partial E^2} \leq 0 \quad . \tag{2}$$

For an ordinary system, the state of zero entropy is reached only at $T=0$. Thus, if $E=0$ is the ground state energy, one has $\frac{\partial S}{\partial E} \to \infty$ for $E \to 0$. For a system exhibiting an ideal glass transition, by definition, $\frac{\partial S}{\partial E}$ is finite as $E \to 0$. These two possibilities are illustrated in Fig. 1. The ideal glass transition of Fig. 1b takes place at $T=T_o$ where

$$\frac{1}{T_o} = \lim_{E \to 0} \frac{\partial S}{\partial E} \quad . \tag{3}$$

Gibbs and DiMarzio [3] originally argued for the existence of an ideal glass transition in polymeric liquids from a study of a lattice model. Several years later it was shown by Gujrati and Goldstein [7] that the mean field approximations made by Gibbs and DiMarzio are incorrect and that, in fact, the lattice model has a positive entropy at any nonzero temperature. But despite this negative result, the Gibbs-DiMarzio idea remains attractive since it offers a simple resolution of the Kauzmann paradox.

The standard example of a system exhibiting an ideal glass transition is Derrida's random energy model (REM) from 1980 [8] (sec. 2). It seems that few other examples exist. This paper studies the "fermi condensation" phenomenon (sec. 3), which has a number of properties in common with the REM. Both models exhibit an ideal glass transition only in a certain limit. The two models also have similar relaxation behavior, as shown in sec. 4.

2. THE RANDOM ENERGY MODEL

This section briefly reviews the random energy model. To motivate this model, expand $S(E)$ to second order in E for a system exhibiting an ideal glass transition (where again it is assumed that the ground state is $E=0$):

$$S(E) = \alpha_1 E - \tfrac{1}{2}\alpha_2 E^2 + \cdots \qquad (4)$$

The function $S(E)$ is the logarithm of the density of states $n(E)$ [6]. Thus, ignoring the higher order terms in Eq. (4) corresponds to assuming a gaussian density of states,

$$n(E) \propto \exp\left[\alpha_1 E - \tfrac{1}{2}\alpha_2 E^2\right] . \qquad (5)$$

The random energy model is now defined simply by choosing N

energy levels randomly from the gaussian [8]. These N energies completely define the system. It is important that N is finite, only after the thermodynamics is worked out is the $N \to \infty$ limit taken. In letting N go to infinity care must be taken to assure that the lowest energy remains close to zero; this is done by varying α_1 appropriately with N [8]. It is easy to see that the resulting model exhibits an ideal glass transition: Close to E=0 the density of states is approximately exponential,

$$n(E) \propto \exp\left[\alpha_1 E\right], \quad (E \cong 0). \tag{6}$$

For $T>T_o$ where $T_o = 1/\alpha_1$, the maximum of the canonical probability, $n(E)\exp(-E/k_BT)$, increases with increasing T. The average energy, $\overline{E}(T)$, is an increasing function of temperature so the specific heat, and thereby the entropy, is positive. Below T_o, on the other hand, the Boltzmann factor dominates over $n(E)$, driving the system to the lowest energy state. Thus, the entropy is zero. Actually, the entropy is only strictly zero in the $N \to \infty$ limit, but even for a finite system there is a sharp decrease in entropy below T_o.

3. FERMICONDENSATION

A system of fermions is usually thought of in terms of occupied and unoccupied states, where it is implied that the

majority of the particles are to be found in occupied states. For some fermisystems, however, this picture is adequate only at low temperatures whereas at higher temperatures most particles are classical, i. e. , have energies for which the average occupation number is << 1 . Consider a system of non-interacting fermions in a "thermodynamic" density of states $g(\varepsilon)$, i. e. , where $S(\varepsilon) = \ln(g(\varepsilon))$ obeys Eq. (2). Expanding $S(\varepsilon)$ around the zero temperature chemical potential (the fermi energy), μ_o , leads to

$$g(\varepsilon) = g_o \exp\left[c_1 (\varepsilon-\mu_o) - \tfrac{1}{2} c_2 (\varepsilon-\mu_o)^2 + \cdots \right] . \qquad (7)$$

At low temperatures most particles have energies close to μ_o. But at higher temperatures the Boltzmann tail of the fermifunction is not able to suppress the $\exp[c_1(\varepsilon-\mu_o)]$ part of $g(\varepsilon)$. The result is that most particles move to higher energies. The particles become classical in the sense that, for the majority of particles, the average occupation number is much less than one. The transition from a fermi to a classical system is continuous and not a sharp transition. It takes place around $T=T_o$ where T_o is given by

$$T_o = \frac{1}{k_B c_1} . \qquad (8)$$

The transition upon cooling from high temperatures may be termed a "fermicondensation", since here the fermisea is formed from the classical gas. The term "gas" is relevant for the high temperature state where the particles effectively do not "interact" via the fermi exclusion principle.

The fermicondensation is signalled by a decrease in specific heat below T_o . In Fig. 2 the specific heat per particle is shown for two different values of $\lambda = c_1/\sqrt{c_2}$ for a system with a gaussian density of states (Eq. (7)). Above T_o most of the fermisea has "evaporated". The particles move independently and each particle has a specific heat of $1/(2k_B T^2 c_2)$, as is easy to show. Below T_o the specific heat per particle is small as in an ordinary fermisystem. For large λ the transition is close to a phase transition. For $\lambda \to \infty$ an ideal glass transition takes place since in this limit the specific heat, and thereby the entropy, vanishes below T_o .

We now briefly discuss relaxation in the model. Assume the simplest possible realistic dynamics, namely that where the jump rate of a fermion depends only on the energy of the initial state [9]. This corresponds to the case where the fermion, once it is excited into the transition state, has forgotten where it came from and may end up in any other (unoccupied) state. If the energy of the transition state is ε_o , the relaxation time for jumps from a state of energy ε is

$$\tau = \tau_o \, e^{\frac{\varepsilon_o - \varepsilon}{k_B T}} \qquad (\varepsilon < \varepsilon_o) \tag{9}$$

where τ_o is a microscopic time. A cut-off at ε_o has been introduced to ensure that no state has larger energy than the transition state. Now, below T_o most particles have energy close to μ_o since the density of states is exponentially increasing. Thus, relaxation is Arrhenius with an activation energy given by

$$\Delta \varepsilon = \varepsilon_0 - \mu_0 \quad (10)$$

Above T_0, the average energy of the particles, $\bar{\varepsilon}$, depends on temperature. Since the particles here move independently, $\bar{\varepsilon}(T)$ is determined by maximizing the probability for one particle having energy ε :

$$\frac{d}{d\varepsilon}\left[g(\varepsilon)\, e^{-\frac{\varepsilon}{k_B T}} \right]\Bigg|_{\varepsilon = \bar{\varepsilon}(T)} = 0. \quad (11)$$

Because $g(\varepsilon)$ is by assumption a thermodynamic density of states, $\bar{\varepsilon}(T)$ is an increasing function of temperature so the activation energy of τ,

$$\Delta \varepsilon = \varepsilon_0 - \bar{\varepsilon}(T), \quad (12)$$

decreases with increasing temperature.

Figure 3 shows a so-called Arrhenius plot of τ, i. e., $\ln(\tau)$ as function of T^{-1}. The behavior of Fig. 3 is like that seen in experiments on the real glass transition. Above the glass transition one observes an average relaxation time which is more than Arrhenius temperature dependent, while in the glassy phase τ is Arrhenius [10]. In experiment, there is furthermore a sudden decrease in the slope of the Arrhenius plot at T_g, just like in Fig. 3. However, one should not attach too much significance to the similarity between fermicondensation and experiments on the real liquid-glass transition. The real glass transition is a kinetic phenomenon and, for instance, the activation energy of in the glassy phase depends on the cooling rate at which the glass

was formed.

4. DISCUSSION

Fermicondensation is an alternative to the random energy model as a model exhibiting an almost ideal glass transition. Unlike the REM, no randomness is invoked in fermicondensation. Therefore, no ensemble averaging is needed to evaluate physical properties like the specific heat, as is necessary for a more accurate treatment of the REM than given here [8]. Since both models involve a gaussian density of states and since the fermions above T_o move independently, the fermisystem behaves like the REM above To . In particular, if the assumption of transition rates being function of the initial energy only is made also for the REM [11], the two models have similar relaxation behavior. Note that the behavior of τ shown in Fig. 3 is valid for the REM even below T_o : Here the REM is in its ground state so the activation energy of τ becomes constant. Thus, the two models are similar both as regards their thermodynamics and their relaxation behavior.

Adam and Gibbs have argued that at an ideal glass transition the average relaxation time becomes infinite because of the few available states to jump into [12]. This argument is still controversial, but this study certainly weakens the Adam-Gibbs hypothesis. In both models relaxation in the glassy phase takes place with a finite relaxation time which is, as a matter of fact, smaller than expected by extrapolating the behavior above T_o .

To summarize, the fermicondensation phenomenon provides an abstract model for the ideal glass transition. No randomness is invoked in the model, but otherwise the model has a number of features in common with the random energy model. The present study of the two models does not confirm the Adams-Gibbs hypothesis concerning a diverging average relaxation time at T_o .

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FIGURE CAPTIONS

Fig. 1: Entropy as function of energy for an ordinary system (Fig. 1a) and for a system exhibiting an ideal glass transition (Fig. 1b). Temperature is defined by $\frac{1}{T} = \frac{\partial S}{\partial E}$ [6] and thermodynamics requires $S(E)$ to be an increasing function of energy with a non-positive second derivative. If $S(E)$ has a finite slope at $E=0$, there is a transition to a state of zero entropy at a positive temperature (Fig. 1b). This is the ideal glass transition, which is a second order phase transition.

Fig. 2: Specific heat per particle as function of temperature for a fixed number of fermions in a gaussian density of states (Eq. (7)). The two curves show the case of (a) $\lambda = 8$ and (b) $\lambda = 20$ where $\lambda = c_1/\sqrt{c_2}$. The specific heat is given in units of $k_B c_1^2/2c_2$. Around $T=T_o$ where T_o is given by Eq. (8) the fermisea "evaporates". Above T_o the fermions behave as independent classical particles, each with a specific heat $\propto T^{-2}$. Upon cooling, the classical gas "condenses" into the fermisea, the fermicondensation.

Fig. 3: Logarithm of the average relaxation time τ plotted as function of inverse temperature in the fermicondensation model where τ is given by Eq. (9) (schematic drawing). Above T_o τ is more than Arrhenius temperature dependent while below T_o τ becomes Arrhenius, much like for the real laboratory glass transition. The activation energy of τ is the slope of the secant

marked by dots (and not the slope of the tangent marked by the punctuated line, as is often assumed). Upon cooling the activation energy of τ increases until T_o is reached. The activation energy then becomes constant. As discussed briefly in sec. 4, the random energy model has a similar relaxation behavior.

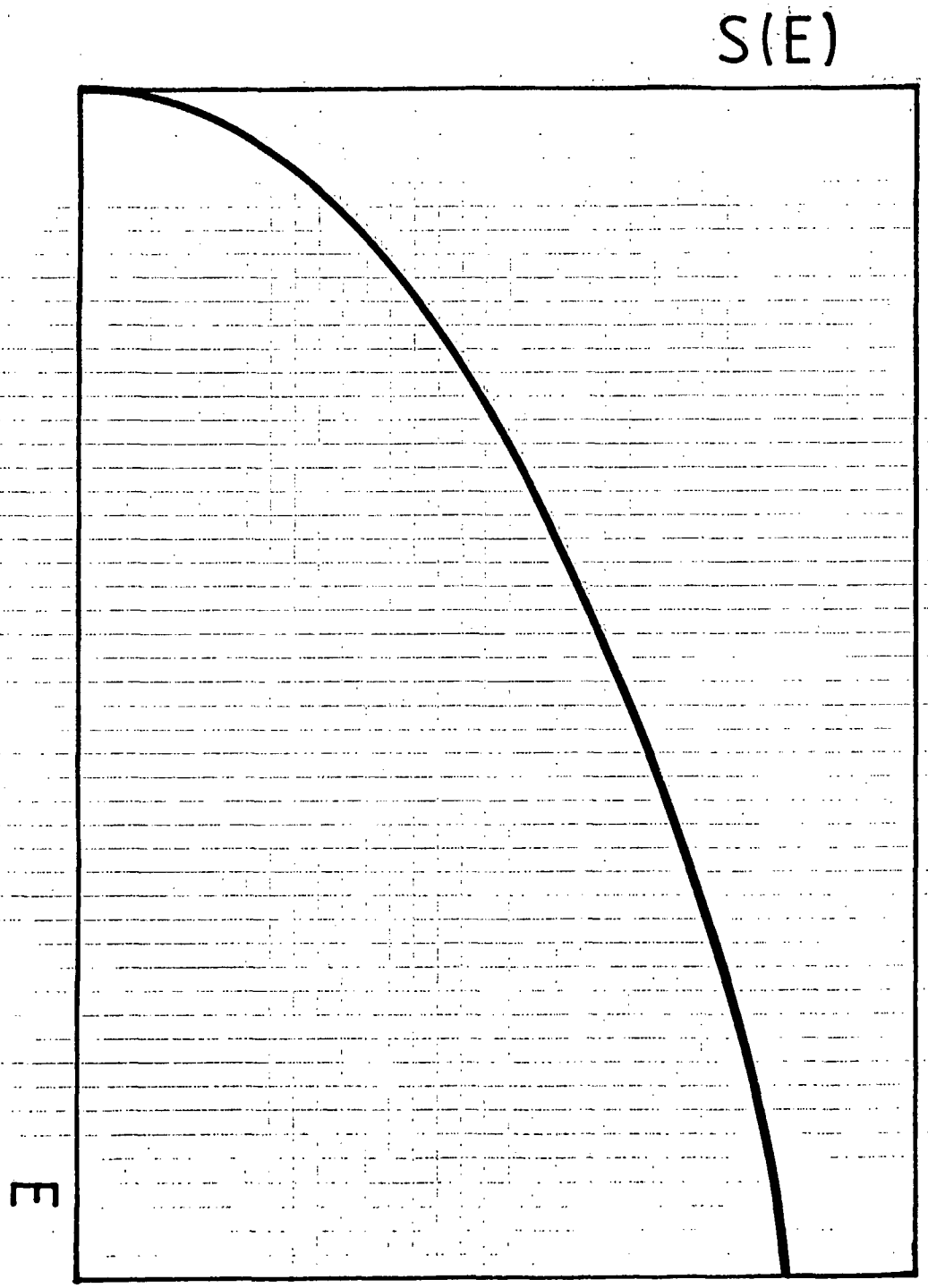


Fig. 1a

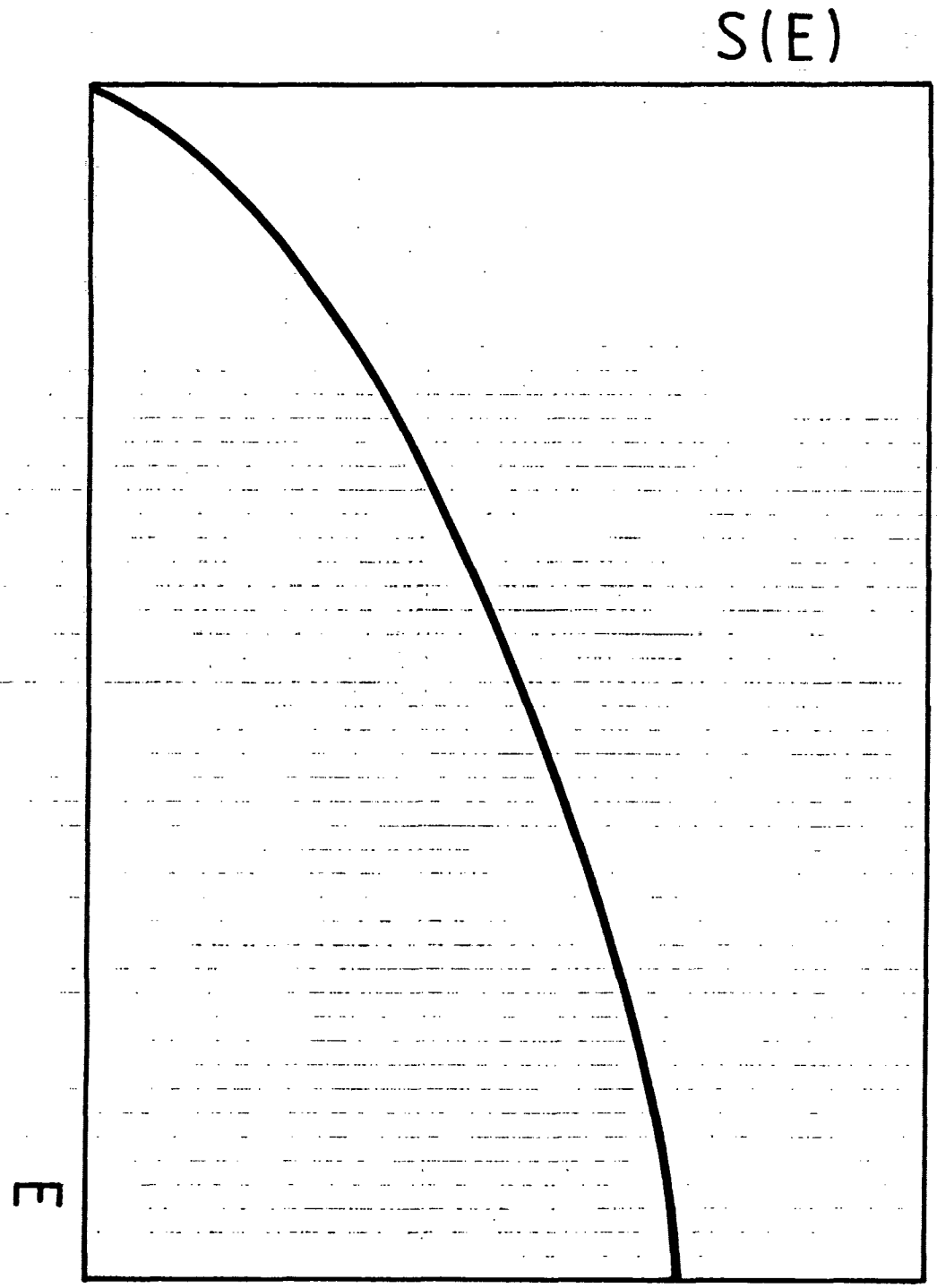


Fig. 11b

Fig. 2

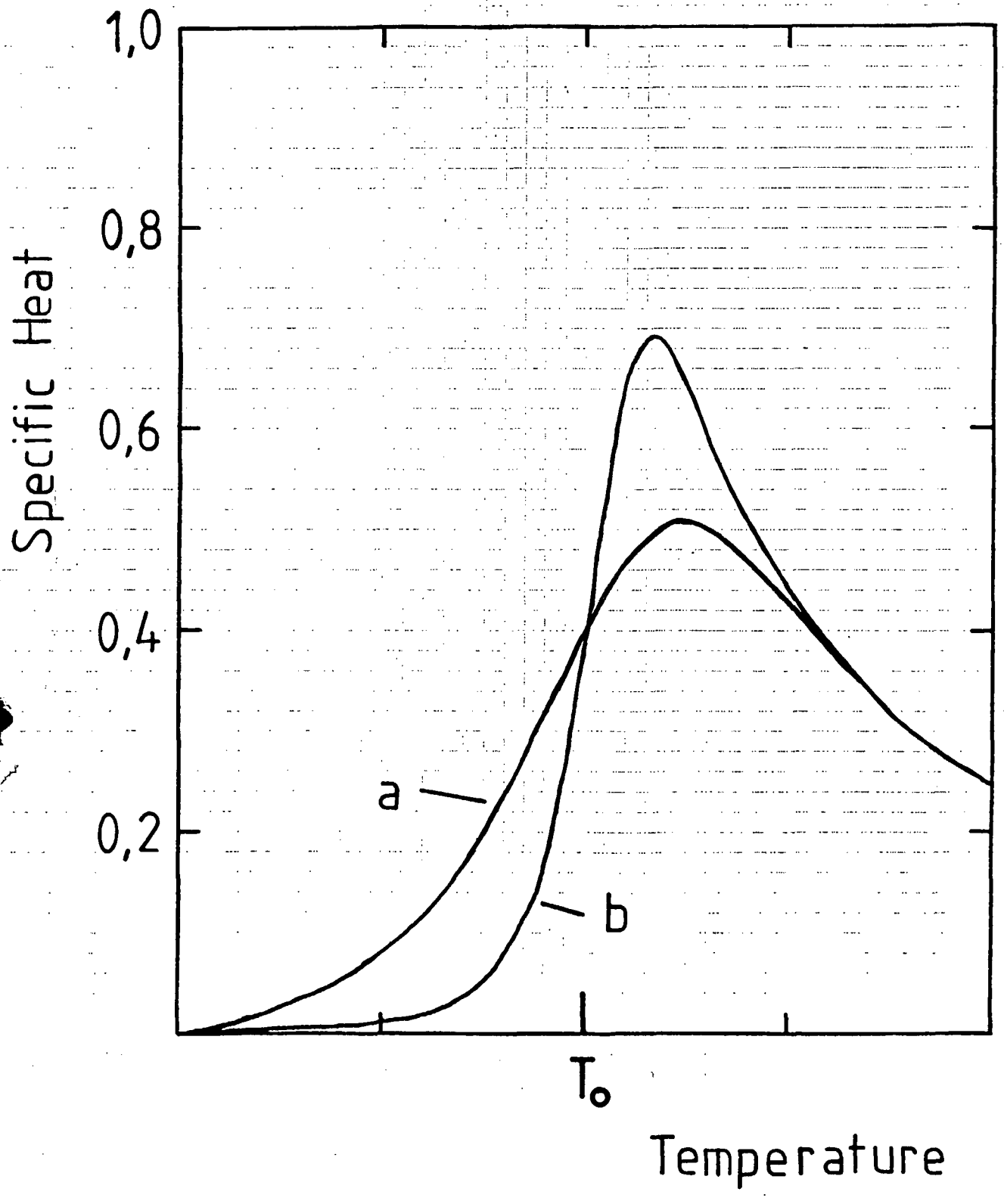
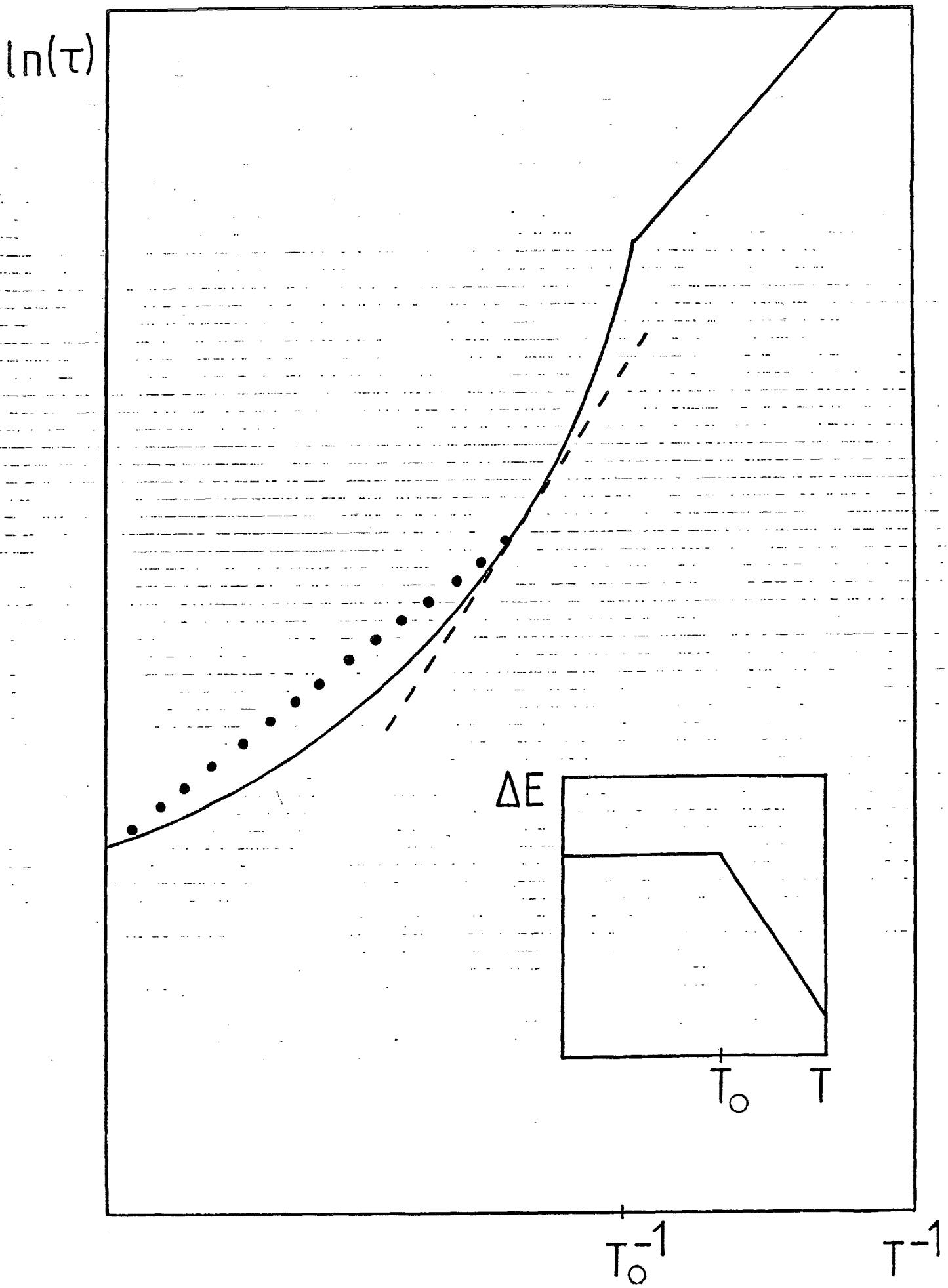


Fig 3

Fig. 3



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61/83 "FYSIKS IDEOLOGISKE FUNKTION, SOM ET EKSEMPEL PÅ EN NATURVIDENSKAB - HISTORISK SET".
Projektrapport af: Annette Post Nielsen.
Vejledere: Jens Høyrup, Jens Højgaard Jensen og Jørgen Vogelius.

62/83 "MATEMATISKE MODELLER" - Litteratur på Roskilde Universitetsbibliotek.
En biografi 2. rev. udgave.
Af: Else Høyrup.

63/83 "GREATING ENERGY FUTURES:A SHORT GUIDE TO ENERGY PLANNING".
ENERGY SERIES No. 8.
Af: David Crossley og Bent Sørensen.

64/83 "VON MATEMATIK UND KRIEG".
Af: Bernhelm Booss og Jens Høyrup.

65/83 "ANVENDT MATEMATIK - TEORI ELLER PRAKSIS".
Projektrapport af: Per Hedegård Andersen, Kirsten Habekost, Carsten Holst-Jensen, Annelise von Moos, Else Marie Pedersen og Erling Møller Pedersen.
Vejledere: Bernhelm Booss og Klaus Grünbaum.

66/83 "MATEMATISKE MODELLER FOR PERIODISK SELEKTION I ESCHERICHIA COLI".
Projektrapport af: Hanne Lisbet Andersen, Ole Richard Jensen og Klavs Frisdahl.
Vejledere: Jørgen Larsen og Anders Hede Madsen.

67/83 "ELEPSOIDE METODEN - EN NY METODE TIL LINEÆR PROGRAMMERING?"
Projektrapport af: Lone Biilmann og Lars Boye.
Vejleder: Mogens Brun Heefelt.

68/83 "STOKASTISKE MODELLER I POPULATIONSGENETIK"
- til kritikken af teoriladede modeller.
Projektrapport af: Lise Odgård Gade, Susanne Hansen, Michael Hviid og Frank Mølgård Olsen.
Vejleder: Jørgen Larsen.

69/83 "ELEVFORUDSÆTNINGER I FYSIK"
- en test i 1.g med kommentarer.
Af: Albert C. Paulsen.

70/83 "INDLÆRINGS - OG FORMIDLINGSPROBLEMER I MATEMATIK PÅ VOKSENUNDERVISNINGSNIVEAU".
Projektrapport af: Hanne Lisbet Andersen, Torben J. Andreasen, Svend Åge Houmann, Helle Glerup Jensen, Keld Fl. Nielsen, Lene Vagn Rasmussen.
Vejleder: Klaus Grünbaum og Anders Hede Madsen.

71/83 "PIGER OG FYSIK"
- et problem og en udfordring for skolen?
Af: Karin Beyer, Sussanne Blegaa, Birthe Olsen, Jette Reich og Mette Vedelsby.

72/83 "VERDEN IFØLGE PEIRCE" - to metafysiske essays, om og af C.S Peirce.
Af: Peder Voetmann Christiansen.

73/83 ""EN ENERGIANALYSE AF LANDBRUG"
- økologisk contra traditionelt.
ENERGY SERIES NO. 9
Specialeopgave i fysik af: Bent Hove Jensen.
Vejleder: Bent Sørensen.

74/84 "MINIATURISERING AF MIKROELEKTRONIK" - om videnskabeliggjort teknologi og nytten af at lære fysik.
Projektrapport af: Bodil Harder og Linda Szkotak Jensen.
Vejledere: Jens Højgaard Jensen og Bent C. Jørgensen.

75/84 "MATEMATIKUNDERVISNINGEN I FREMTIDENS GYMNASIUM"
- Case: Lineær programmering.
Projektrapport af: Morten Blomhøj, Klavs Frisdahl og Frank Mølgaard Olsen.
Vejledere: Mogens Brun Heefelt og Jens Bjørneboe.

76/84 "KERNEKRAFT I DANMARK?" - Et høringssvar indkaldt af miljøministeriet, med kritik af miljøstyrelsens rapporter af 15. marts 1984.
ENERGY SERIES No. 10
Af: Niels Boye Olsen og Bent Sørensen.

77/84 "POLITISKE INDEKS - FUP ELLER FAKTA?"
Opinionsundersøgelser belyst ved statistiske modeller.
Projektrapport af: Svend Åge Houmann, Keld Nielsen og Susanne Stender.
Vejledere: Jørgen Larsen og Jens Bjørneboe.

78/84 "JÆVNSTRØMSLEDNINGSEVNE OG GITTERSTRUKTUT I AMORFT GERMANIUM".
Specialrapport af: Hans Hedal, Frank C. Ludvigsen og Finn C. Physant.
Vejleder: Niels Boye Olsen.

79/84 "MATEMATIK OG ALMENDANNELSE".
Projektrapport af: Henrik Coster, Mikael Wennerberg Johansen, Povl Kattler, Birgitte Lydholm og Morten Overgaard Nielsen.
Vejleder: Bernhelm Booss.

80/84 "KURSUSMATERIALE TIL MATEMATIK B".
Af: Mogens Brun Heefelt.

81/84 "FREKVENSAFHÆNGIG LEDNINGSEVNE I AMORFT GERMANIUM".
Specialerapport af: Jørgen Wind Petersen og Jan Christensen.
Vejleder: Niels Boye Olsen.

82/84 "MATEMATIK - OG FYSIKUNDERVISNINGEN I DET AUTOMATISEREDE SAMFUND".
Rapport fra et seminar afholdt i Hvidovre 25-27 april 1983.
Red.: Jens Højgaard Jensen, Bent C. Jørgensen og Mogens Niss.

83/84 "ON THE QUANTIFICATION OF SECURITY":
PEACE RESEARCH SERIES NO. 1
Af: Bent Sørensen
nr. 83 er p.t. udgået

84/84 "NOGLE ARTIKLER OM MATEMATIK, FYSIK OG ALMENDANNELSE".
Af: Jens Højgaard Jensen, Mogens Niss m. fl.

85/84 "CENTRIFUGALREGULATORER OG MATEMATIK".
Specialerapport af: Per Hedegård Andersen, Carsten Holst-Jensen, Else Marie Pedersen og Erling Møller Pedersen.
Vejleder: Stig Andur Pedersen.

86/84 "SECURITY IMPLICATIONS OF ALTERNATIVE DEFENSE OPTIONS FOR WESTERN EUROPE".
PEACE RESEARCH SERIES NO. 2
Af: Bent Sørensen.

87/84 "A SIMPLE MODEL OF AC HOPPING CONDUCTIVITY IN DISORDERED SOLIDS".
Af: Jeppe C. Dyre.

88/84 "RISE, FALL AND RESURRECTION OF INFINITESIMALS".
Af: Detlef Laugwitz.

89/84 "FJERNVARMEOPTIMERING".
Af: Bjarne Lillethorup og Jacob Mørch Pedersen.

90/84 "ENERGI I 1.G - EN TEORI FOR TILRETTELÆGGELSE".
Af: Albert Chr. Paulsen.

91/85 "KVANTETEORI FOR GYMNASIET".
1. Lærervejledning
Projektrapport af: Biger Lundgren, Henning Sten Hansen og John Johansson.
Vejleder: Torsten Meyer.

92/85 "KVANTETEORI FOR GYMNASIET".
2. Materiale
Projektrapport af: Biger Lundgren, Henning Sten Hansen og John Johansson.
Vejleder: Torsten Meyer.

93/85 "THE SEMIOTICS OF QUANTUM - NON - LOCALITY".
Af: Peder Voetmann Christiansen.

94/85 "TREENIGHEDEN BOURBAKI - generalen, matematikeren og ånden".
Projektrapport af: Morten Blomhøj, Klavs Frisdahl og Frank M. Olsen.
Vejleder: Mogens Niss.

95/85 "AN ALTERNATIV DEFENSE PLAN FOR WESTERN EUROPE".
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Af: Bent Sørensen

96/85 "ASPEKTER VED KRAFTVARMEFORSYNING".
Af: Bjarne Lilletorup.
Vejleder: Bent Sørensen.

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Af: Jeppe C. Dyre.

98/85 "VALGMULIGHEDER I INFORMATIONSALDEREN".
Af: Bent Sørensen.

99/85 "Der er langt fra Q til R".
Projektrapport af: Niels Jørgensen og Mikael Klintorp.
Vejleder: Stig Andur Pedersen.

100/85 "TALSYSTEMETS OPBYGNING".
Af: Mogens Niss.

101/85 "EXTENDED MOMENTUM THEORY FOR WINDMILLS IN PERTURBATIVE FORM".
Af: Ganesh Sengupta.

102/85 OPSTILLING OG ANALYSE AF MATEMATISKE MODELLER, BELYST VED MODELLER OVER KØERS FODEROPTAGELSE OG - OMSÆTNING".
Projektrapport af: Lis Eilertzen, Kirsten Habekost, Lill Røn og Susanne Stender.
Vejleder: Klaus Grünbaum.

103/85 "ØDSLE KOLDKRIGERE OG VIDENSKABENS LYSE IDEER".
Projektrapport af: Niels Ole Dam og Kurt Jensen.
Vejleder: Bent Sørensen.

104/85 "ANALOGREGNEMASKINEN OG LORENZLIGNINGER".
Af: Jens Jæger.

105/85 "THE FREQUENCY DEPENDENCE OF THE SPECIFIC HEAT AF THE GLASS REANSITION".
Af: Tage Christensen.

"A SIMPLE MODEL AF AC HOPPING CONDUCTIVITY".
Af: Jeppe C. Dyre.
Contributions to the Third International Conference on the Structure of Non - Crystalline Materials held in Grenoble July 1985.

106/85 "QUANTUM THEORY OF EXTENDED PARTICLES".
Af: Bent Sørensen.

107/85 "EN MYG GØR INGEN EPIDEMI"
- flodblindhed som eksempel på matematisk modellering af et epidemiologisk problem.
Projektrapport af: Per Hedegård Andersen, Lars Boye, CarstenHolst Jensen, Else Marie Pedersen og Erling Møller Pedersen.
Vejleder: Jesper Larsen.

108/85 "APPLICATIONS AND MODELLING IN THE MATEMATICS CURRICULUM" - state and trends -
Af: Mogens Niss.

109/85 "COX I STUDIETIDEN" - Cox's regressionsmodel anvendt på studenteroplysninger fra RUC.
Projektrapport af: Mikael Wennerberg Johansen, Poul Katler og Torben J. Andreasen.
Vejleder: Jørgen Larsen.

110/85 "PLANNING FOR SECURITY".
Af: Bent Sørensen

111/85 JORDEN RUNDT PÅ FLADE KORT".
Projektrapport af: Birgit Andresen, Beatriz Quinones og Jimmy Staal.
Vejleder: Mogens Niss.

112/85 "VIDENSKABELIGGØRELSE AF DANSK TEKNOLOGISK INNOVATION FREM TIL 1950 - BELYST VED EKSEMPLER".
Projektrapoort af: Erik Odgaard Gade, Hans Hedal, Frank C. Ludvigsen, Annette Post Nielsen og Finn Physant.
Vejleder: Claus Bryld og Bent C. Jørgensen.

113/85 "DESUSPENSION OF SPLITTING ELLIPTIC SYMBOLS 11".
Af: Bernhelm Booss og Krzysztof Wojciechowski.

114/85 "ANVENDELSE AF GRAFISKE METODER TIL ANALYSE AF KONTIGENSTABELLER".
Projektrapport af: Lone Biilmann, Ole R. Jensen og Arne-Lise von Moos.
Vejleder: Jørgen Larsen.

115/85 "MATEMATIKKENS UDVIKLING OP TIL RENÆSSANCEN".
Af: Mogens Niss.

116/85 "A PHENOMENOLOGICAL MODEL FOR THE MEYER-NELDEL RULE".
Af: Jeppe C. Dyre.

117/85 "KRAFT & FJERNVARMEOPTIMERING"
Af: Jacob Mørch Pedersen.
Vejleder: Bent Sørensen

118/85 "TILFÆLDIGHEDEN OG NØDVENDIGHEDEN IFØLGE PEIRCE OG FYSIKKEN".
Af: Peder Voetmann Christiansen

119/86 "DET ER GANSKE VIST - - EUKLIDS FEMTE POSTULAT KUNNE NOK SKABE RØRE I ANDEDAMMEN".
Af: Iben Maj Christiansen
Vejleder: Mogens Niss.

120/86 "ET ANTAL STATISTISKE STANDARDMODELLER".
Af: Jørgen Larsen

121/86 "SIMULATION I KONTINUERT TID".
Af: Peder Voetmann Christiansen.

122/86 "ON THE MECHANISM OF GLASS IONIC CONDUCTIVITY".
Af: Jeppe C. Dyre.

123/86 "GYMNASIEFYSIKKEN OG DEN STORE VERDEN".
Fysiklærerforeningen, IMFUFA, RUC.

124/86 "OPGAVESAMLING I MATEMATIK".
Samtlige opgaver stillet i tiden 1974-jan. 1986.

125/86 "UVBY,β - systemet - en effektiv fotometrisk spektralklassifikation af B-,A- og F-stjerner".
Projektrapport af: Birger Lundgren.

126/86 "OM UDVIKLINGEN AF DEN SPECIELLE RELATIVITETSTEORI".
Projektrapport af: Lise Odgaard & Linda Szkotak Jensen
Vejledere: Karin Beyer & Stig Andur Pedersen.

127/86 "GALOIS' BIDRAG TIL UDVIKLINGEN AF DEN ABSTRAKTE ALGEBRA".
Projektrapport af: Pernille Sand, Heine Larsen & Lars Frandsen.
Vejleder: Mogens Niss.

128/86 "SMÅKRYB" - om ikke-standard analyse.
Projektrapport af: Niels Jørgensen & Mikael Klintorp.
Vejleder: Jeppe Dyre.

129/86 "PHYSICS IN SOCIETY"
Lecture Notes 1983 (1986)
Af: Bent Sørensen

130/86 "Studies in Wind Power"
Af: Bent Sørensen

131/86 "FYSIK OG SAMFUND" - Et integreret fysik/historieprojekt om naturanskuelsens historiske udvikling og dens samfundsmæssige betingethed.
Projektrapport af: Jakob Heckscher, Søren Brønd, Andy Wierød.
Vejledere: Jens Høyrup, Jørgen Vogelius, Jens Højgaard Jensen.

132/86 "FYSIK OG DANNELSE"
Projektrapport af: Søren Brønd, Andy Wierød.
Vejledere: Karin Beyer, Jørgen Vogelius.

133/86 "CHERNOBYL ACCIDENT: ASSESSING THE DATA.
ENERGY SERIES NO. 15.
AF: Bent Sørensen.

134/87 "THE D.C. AND THE A.C. ELECTRICAL TRANSPORT IN AsSeTe SYSTEM"
Authors: M.B.El-Den, N.B.Olsen, Ib Høst Pedersen, Petr Viščor

135/87 "INTUITIONISTISK MATEMATIKS METODER OG ERKENDELSESTEORETISKE FORUDSÆTNINGER"
MASTEMATIKSPECIALE: Claus Larsen
Vejledere: Anton Jensen og Stig Andur Pedersen

136/87 "Mystisk og naturlig filosofi: En skitse af kristendommens første og andet møde med græsk filosofi"
Projektrapport af Frank Colding Ludvigsen
Vejledere: Historie: Ib Thiersen
Fysik: Jens Højgaard Jensen

137/87 "HOPMODELLER FOR ELEKTRISK LEDNING I UORDNEDE FASTE STOFFER" - Resume af licentiatafhandling
Af: Jeppe Dyre
Vejledere: Niels Boye Olsen og Peder Voetmann Christiansen.

138/87 "JOSEPHSON EFFECT AND CIRCLE MAP."

Paper presented at The International Workshop on Teaching Nonlinear Phenomena at Universities and Schools, "Chaos in Education". Balaton, Hungary, 26 April-2 May 1987.

By: Peder Voetmann Christiansen

139/87 "Machbarkeit nichtbeherrschbarer Technik durch Fortschritte in der Erkennbarkeit der Natur"

Af: Bernhelm Booss-Bavnbek
Martin Bohle-Carbonell

140/87 "ON THE TOPOLOGY OF SPACES OF HOLOMORPHIC MAPS"

By: Jens Gravesen

141/87 "RADIOMETERS UDVIKLING AF BLODGASAPPARATUR - ET TEKNOLOGIHISTORISK PROJEKT"

Projektrapport af Finn C. Physant

Vejleder: Ib Thiersen

142/87 "The Calderón Projektor for Operators With Splitting Elliptic Symbols"

by: Bernhelm Booss-Bavnbek og
Krzysztof P. Wojciechowski

143/87 "Kursusmateriale til Matematik på NAT-BAS"

af: Mogens Brun Heefelt

144/87 "Context and Non-Locality - A Peircan Approach

Paper presented at the Symposium on the Foundations of Modern Physics The Copenhagen Interpretation 60 Years after the Como Lecture. Joensuu, Finland, 6 - 8 august 1987.

By: Peder Voetmann Christiansen

145/87 "AIMS AND SCOPE OF APPLICATIONS AND MODELLING IN MATHEMATICS CURRICULA"

Manuscript of a plenary lecture delivered at ICMTA 3, Kassel, FRG 8.-11.9.1987

By: Mogens Niss

146/87 "BESTEMMELSE AF BULKRESISTIVITETEN I SILICIUM"

- en ny frekvensbaseret målemetode.

Fysikspeciale af Jan Vedde

Vejledere: Niels Boye Olsen & Petr Viščor

147/87 "Rapport om BIS på NAT-BAS"

redigeret af: Mogens Brun Heefelt

148/87 "Naturvidenskabsundervisning med Samfundsperspektiv"

af: Peter Colding-Jørgensen DLH
Albert Chr. Paulsen

149/87 "In-Situ Measurements of the density of amorphous germanium prepared in ultra high vacuum"

by: Petr Viščor

150/87 "Structure and the Existence of the first sharp diffraction peak in amorphous germanium prepared in UHV and measured in-situ"

by: Petr Viščor

151/87 "DYNAMISK PROGRAMMERING"

Matematikprojekt af:
Birgit Andresen, Keld Nielsen og Jimmy Staal

Vejleder: Mogens Niss

152/87 "PSEUDO-DIFFERENTIAL PROJECTIONS AND THE TOPOLOGY OF CERTAIN SPACES OF ELLIPTIC BOUNDARY VALUE PROBLEMS"

by: Bernhelm Booss-Bavnbek
Krzysztof P. Wojciechowski

153/88 "HALVLEDERTEKNOLOGIENS UDVIKLING MELLEM MILITÆRE OG CIVILE KRÆFTER"

Et eksempel på humanistisk teknologihistorie
Historiespeciale

Af: Hans Hedal

Vejleder: Ib Thiersen

154/88 "MASTER EQUATION APPROACH TO VISCOUS LIQUIDS AND THE GLASS TRANSITION"

By: Jeppe Dyre

155/88 "A NOTE ON THE ACTION OF THE POISSON SOLUTION OPERATOR TO THE DIRICHLET PROBLEM FOR A FORMALLY SELFADJOINT DIFFERENTIAL OPERATOR"

by: Michael Pedersen

156/88 "THE RANDOM FREE ENERGY BARRIER MODEL FOR AC CONDUCTION IN DISORDERED SOLIDS"

by: Jeppe C. Dyre

157/88 " STABILIZATION OF PARTIAL DIFFERENTIAL EQUATIONS BY FINITE DIMENSIONAL BOUNDARY FEEDBACK CONTROL: A pseudo-differential approach."

by: Michael Pedersen

158/88 "UNIFIED FORMALISM FOR EXCESS CURRENT NOISE IN RANDOM WALK MODELS"

by: Jeppe Dyre

159/88 "STUDIES IN SOLAR ENERGY"

by: Bent Sørensen

160/88 "LOOP GROUPS AND INSTANTONS IN DIMENSION TWO"

by: Jens Gravesen

161/88 "PSEUDO-DIFFERENTIAL PERTURBATIONS AND STABILIZATION OF DISTRIBUTED PARAMETER SYSTEMS:

Dirichlet feedback control problems"

by: Michael Pedersen

162/88 "PIGER & FYSIK - OG MEGET MERE"

AF: Karin Beyer, Sussanne Blegaa, Birthe Olsen,
Jette Reich , Mette Vedelsby

163/88 "EN MATEMATISK MODEL TIL BESTEMMELSE AF PERMEABILITETEN FOR BLOD-NETHINDE-BARRIEREN"

Af: Finn Langberg, Michael Jarden, Lars Frellesen

Vejleder: Jesper Larsen

164/88 "Vurdering af matematisk teknologi
Technology Assessment
Technikfolgenabschätzung"

Af: Bernhelm Booss-Bavnbek, Glen Pate med
Martin Bohle-Carbonell og Jens Højgaard Jensen

165/88 "COMPLEX STRUCTURES IN THE NASH-MOSER CATEGORY"

by: Jens Gravesen

166/88 "Grundbegreber i Sandsynligheds-regningen"

Af: Jørgen Larsen

167a/88 "BASISSTATISTIK 1. Diskrete modeller"

Af: Jørgen Larsen

167b/88 "BASISSTATISTIK 2. Kontinuerte modeller"

Af: Jørgen Larsen

168/88 "OVERFLADEN AF PLANETEN MARS"
Laboratorie-simulering og MARS-analoger undersøgt ved Mössbauerspektroskopi.

Fysikspeciale af:

Birger Lundgren

Vejleder: Jens Martin Knudsen
Fys.Lab./HCØ

169/88 "CHARLES S. PEIRCE: MURSTEN OG MØRTEL TIL EN METAFYSIK."

Fem artikler fra tidsskriftet "The Monist" 1891-93.

Introduktion og oversættelse:

Peder Voetmann Christiansen

170/88 "OPGAVESAMLING I MATEMATIK"

Samtlige opgaver stillet i tiden 1974 - juni 1988

171/88 "The Dirac Equation with Light-Cone Data"

af: Johnny Tom Ottesen

172/88 "FYSIK OG VIRKELIGHED"

Kvantemekanikkens grundlagsproblem i gymnasiet.

Fysikprojekt af:

Erik Lund og Kurt Jensen

Vejledere: Albert Chr. Paulsen og Peder Voetmann Christiansen

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173/89 "NUMERISKE ALGORITMER"

af: Mogens Brun Heefelt

174/89 " GRAFISK FREMSTILLING AF FRAKTALER OG KAOS"

af: Peder Voetmann Christiansen

175/89 " AN ELEMENTARY ANALYSIS OF THE TIME DEPENDENT SPECTRUM OF THE NON-STATONARY SOLUTION TO THE OPERATOR RICCATI EQUATION

af: Michael Pedersen

176/89 " A MAXIUM ENTROPY ANSATZ FOR NONLINEAR RESPONSE THEORY"

af : Jeppe Dyre

177/89 "HVAD SKAL ADAM STÅ MODEL TIL"

af: Morten Andersen, Ulla Engström, Thomas Gravesen, Nanna Lund, Pia Madsen, Dina Rawat, Peter Torstensen

Vejleder: Mogens Brun Heefelt

178/89 "BIOSYNTESEN AF PENICILLIN - en matematisk model"

af: Ulla Eghave Rasmussen, Hans Oxvang Mortensen, Michael Jarden

vejleder i matematik: Jesper Larsen
biologi: Erling Lauridsen

179a/89 "LÆRERVEJLEDNING M.M. til et eksperimentelt forløb om kaos"

af: Andy Wierød, Søren Brønd og Jimmy Staal

Vejledere: Peder Voetmann Christiansen
Karin Beyer

179b/89 "ELEVHÆFTE: Noter til et eksperimentelt kursus om kaos"

af: Andy Wierød, Søren Brønd og Jimmy Staal

Vejledere: Peder Voetmann Christiansen
Karin Beyer

180/89 "KAOS I FYSISKE SYSTEMER eksemplificeret ved torsions- og dobbeltpendul".

af: Andy Wierød, Søren Brønd og Jimmy Staal

181/89 "A ZERO-PARAMETER CONSTITUTIVE RELATION FOR PURE SHEAR VISCOELASTICITY"

by: Jeppe Dyre

182/89 "OPGAVESAMLING - BREDDE-KURSUS I FYSIK"

Ny udgave, der erstatter Tekst Nr. 3/1978.

af: **Karin Beyer, Jens Højgaard Jensen, Albert Chr. Paulsen m.fl.**

183/89 "MATEMATICAL PROBLEM SOLVING, MODELLING. APPLICATIONS AND LINKS TO OTHER SUBJECTS - State. trends and issues in mathematics instruction

by: **WERNER BLUM, Kassel (FRG) og MOGENS NISS, Roskilde (Denmark)**

184/89 "En metode til bestemmelse af den frekvensafhængige varmefylde af en underafkølet væske ved glasovergangen"

af: Tage Emil Christensen

185/90 "EN NÆSTEN PERIODISK HISTORIE"

Et matematisk projekt

af: Steen Grode og Thomas Jessen

Vejleder: Jacob Jacobsen

186/90 "RITUAL OG RATIONALITET i videnskabers udvikling"

redigeret af Arne Jakobsen og Stig Andur Pedersen

187/90 "RSA - et kryptisk system"

af: Annemette Sofie Olufsen, Lars Frellesen og Ole Møller Nielsen

Vejledere: Michael Pedersen og Finn Munk

188/90 "FERMICONDENSATION - AN ALMOST IDEAL GLASS TRANSITION"

by: Jeppe Dyre