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A MAXIMUM ENTROPY ANSATZ FOR NONLINEAR RESPONSE THEORY

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Abstract:

An approximate nonlinear response theory is derived by maximizing the information theoretic entropy in the space of fluctuations $J(t)$ of the degree of freedom of interest, subject to constant energy dissipation in the external field. The resulting formalism expresses all cumulant averages of $J(t)$ in an external field in terms of equilibrium averages.

Linear response theory [1-7] is fundamental to much present day work in solid state physics, chemical physics, plasma physics, etc. Its usefulness rests in the fact that the response to an external field to first order is determined solely by an equilibrium autocorrelation function. The extension of linear response theory to include higher order terms was discussed already in the 1950's [6,8]. In contrast to the linear case, the higher order terms cannot be expressed in terms of equilibrium correlation functions of the degree of freedom under consideration [9]. The exact nonlinear response theory is complex and has found little application. There is also the question of the convergence of the formal expansion in the external field. Strong fields may induce e. g. phase transitions or self organization, information about which one does not expect to be hidden in the equilibrium fluctuations. Despite these reservations, one may ask whether a theory which predicts the nonlinear response from equilibrium fluctuations does exist, at least as a reasonable approximation applicable not too far from equilibrium. In an attempt to answer this question, this paper discusses and generalizes a little known ansatz for "non-linear response theory", due to Stratonovich [10]. The ansatz is here derived from the maximum entropy principle. Some simple examples are given and the validity of the ansatz is discussed. It is argued that the ansatz represents, in a sense, the simplest way a system may become nonlinear.

The degree of freedom of interest is denoted by Q, it may be microscopic or macroscopic. The underlying dynamics is assumed to be classical and Q is assumed to be invariant under time-reversal. Q couples to an external field E via a term $-EQ$ in the Hamiltonian. Only the case of a time-independent external

field will be considered. It is convenient to discuss response and fluctuations in terms of $J(t) \equiv \dot{Q}(t)$. In general, one is interested in not only the average $\langle J \rangle_E$ but also in the external field autocorrelation function and perhaps higher order averages. To calculate these quantities one needs to know the probability of any $J(t)$-fluctuation in the external field, $P_E[J(t)]$. As mentioned above, even a complete knowledge of the equilibrium fluctuations, $P_o[J(t)]$, in general is not enough to determine $P_E[J(t)]$. The task of finding $P_E[J(t)]$ may be viewed as a missing information problem. In an external field there is a certain rate of energy dissipation, and no more than this and $P_o[J(t)]$ is known a priori. The maximum entropy formalism is a general method that, based on the insufficient information available, gives a least biased estimate of probabilities [11, 12]. In applications to a continuous problem a reference measure is needed. In the present case, in order to have a smooth transition to the zero field case this measure must be $P_o[J(t)]$. The maximum entropy requirement leads to [11, 12]

$$P_E[J(t)] = N^{-1} P_o[J(t)] \exp\left\{-\lambda E \int_{-\infty}^{\infty} J(t)\,dt\right\} \qquad (1)$$

where N is a normalization constant and $\lambda = \lambda(E)$ is a Lagrangian multiplier. Normally, one would now proceed to determine λ from the constraint, i. e. the energy dissipation rate. In this case, however, λ is *determined by fundamental requirements of* statistical mechanics. As shown by Bochkov and Kuzovlev [13, 14], the time-reversal invariance of the microscopic equations of motion implies

$$\frac{P_E[J(t)]}{P_E[-J(-t)]} = \exp\left\{\beta E \int_{-\infty}^{\infty} J(t)\,dt\right\} \qquad (2)$$

where β is the inverse temperature. Equation (2) is derived by assuming thermal equilibrium at $t=-\infty$ followed by a decoupling of the heat bath and evolution according to the canonical equations of motion for the system interacting with the external field. Alternatively, the heat bath may be thought of as part of the system. These assumptions are identical to those used by Kubo in deriving linear response theory [6]. Equation (2) is also valid for any system which is described by a master equation; in this case Eq. (2) follows from the principle of detailed balance. Since $P_0[J(t)]$ is time-reversal invariant, Eqs. (1) and (2) imply $\lambda=-\beta/2$ for all E , i. e.

$$P_E[J(t)] = N^{-1} P_0[J(t)] \exp\left\{\beta/2\, E \int_{-\infty}^{\infty} J(t)\, dt\right\}. \tag{3}$$

Equation (3) allows one to calculate all higher order cumulant averages of J in the external field, in terms of equilibrium cumulants. The cumulants are defined by the generating functional

$$D[u(\tau);E] = \ln\left\langle \exp\left\{\int_{-\infty}^{\infty} u(\tau) J(\tau)\, d\tau\right\}\right\rangle_E$$

$$= \sum_{n=1}^{\infty} \frac{1}{n!} \int_{-\infty}^{\infty} dt_1 \cdots dt_n \left\langle J(t_1), \cdots, J(t_n)\right\rangle_E u(t_1)\cdots u(t_n) \tag{4}$$

and Eq. (3) implies

$$D[u(\tau);E] = D[u(\tau)+\beta/2\, E; 0] - D[\beta/2\, E; 0]. \tag{5}$$

From Eq. (5) the nonequilibrium cumulants may be found as derivatives with respect to $u(\tau)$ at $u\equiv 0$.

For the average of J one finds from Eq. (5)

$$\langle J\rangle_E = \sum_{n=0}^{\infty} \frac{1}{n!}\left(\frac{\beta E}{2}\right)^n \int_{-\infty}^{\infty} dt_1 \cdots dt_n \langle J(0), J(t_1), \cdots, J(t_n)\rangle_0 \ . \qquad (6)$$

The first order term is that predicted by linear response theory. Note that, for a macroscopic Q, Eq. (6) is consistent in the thermodynamic limit since cumulants are additive for independently fluctuating quantities. An identity for the $(n+1)$'th cumulant average of $\Delta Q(t) = Q(t)-Q(0)$, $\lim_{t\to\infty} t^{-1}\langle \Delta Q^{(n+1)}(t)\rangle_0 = \int_{-\infty}^{\infty} dt_1 \cdots dt_n \langle J(0), J(t_1), \cdots, J(t_n)\rangle_0$, allows one to rewrite Eq. (6) as

$$\langle J\rangle_E = \lim_{t\to\infty} t^{-1} \frac{d}{du} \ln \left\langle e^{u\Delta Q(t)}\right\rangle_0 \Big|_{u=\beta/2 E} \ . \qquad (7)$$

As a simple example of Eq. (7), consider a particle performing a random walk in one dimension on a lattice with lattice constant a. Q is the coordinate and J the velocity of the particle. If there are N jumps in time t it is easy to see that $\langle e^{u\Delta Q(t)}\rangle_0 = \cosh^N(ua)$. Since N is Poisson distributed around a mean $\bar{N}=\Gamma t$, one has

$$\left\langle e^{u\Delta Q(t)}\right\rangle_0 = e^{-\bar{N}} \sum_{N=0}^{\infty} \frac{\bar{N}^N}{N!} \cosh^N(ua) = e^{\bar{N}(\cosh(ua)-1)} \qquad (8)$$

which implies

$$\langle v\rangle_E = \Gamma a \sinh(\beta/2 E a). \qquad (9)$$

This is the correct result if the random walk is realized as the low temperature limit of a particle in a symmetric periodic potential obeying a Langevin equation; the well-known Eq. (9) follows from the fact that the field lowers the barrier for jumps

in the direction of E and increases the barrier for jumps opposite to E. As another example of Eq. (7), consider the case when Q is the x-coordinate of an atom in a liquid. Then Eq. (7) expresses the velocity of the atom in a field in the x-direction acting only on the atom, in terms of the equilibrium incoherent intermediate scattering function $F_s(k,t)$:

$$\langle v \rangle_E = \lim_{t\to\infty} (it)^{-1} \frac{\partial}{\partial k} \ln F_s(k,t)\Big|_{k=\frac{\beta E}{2i}} \qquad (10)$$

For simple gaussian diffusion $F_s(k,t)=\exp(-Dk^2t)$ [15]. In this case the response is exactly linear and Eq. (10) reduces to the Nernst-Einstein relation between mobility and diffusion constant. A more realistic fit to experiment is the prediction of the jump-diffusion model [15, 16] $F_s(k,t) = \exp[-Dk^2t/(1+Dk^2\tau_o)]$. From this, Eq. (10) predicts the onset of nonlinearity at fields for which $El\beta \simeq 1$ where the length $l=\sqrt{D\tau_o}$ in fits to data is of order one interatomic spacing.

For the external field autocorrelation function Eq. (5) implies

$$\langle J(0), J(t)\rangle_E = \langle J(0), J(t)\rangle_0 + \frac{\beta E}{2}\int_{-\infty}^{\infty} dt_1 \langle J(0), J(t), J(t_1)\rangle_0$$
$$+ \frac{1}{2}\left(\frac{\beta E}{2}\right)^2 \iint_{-\infty}^{\infty} dt_1\, dt_2 \langle J(0), J(t), J(t_1), J(t_2)\rangle_0 + \cdots \qquad (11)$$

An example is the case when J is the electric current. For a system with frequency-independent conductivity the zeroth order term is a delta function, giving rise to white noise. In most cases the next term is zero by symmetry and the so-called excess current noise is given by the second order term. Excess current noise is ubiquitous and usually has a 1/f spectrum [17-19]. A

number of random walk models have been studied to gain a better understanding of the phenomenon. In these models one finds [20-23]

$$\langle J(0), J(t)\rangle_E = (\beta E)^2 \int_0^t dt_2 \int_0^{t_2} dt_1 \langle J(0), J(t), J(t_1), J(t_2)\rangle_0 + \cdots \quad (t>0) \tag{12}$$

which is equivalent to Eq. (11) because in random walk models $\langle J(t_1), J(t_2), J(t_3), J(t_4)\rangle$ is non-zero only if $t_1 \approx t_2$ and $t_3 \approx t_4$ (or permutations thereof) where $t_1 \approx t_2$ means $t_1 - t_2$ is a microscopic time [20,21].

The similarity between the right hand sides of Eqs. (6) and (11) suggests that a relation exists between $\langle J\rangle_E$ and $\langle J(0), J(t)\rangle_E$. It is easy to show that

$$\frac{d}{dE}\langle J\rangle_E = \frac{\beta}{2}\int_{-\infty}^{\infty} \langle J(0), J(t)\rangle_E \, dt. \tag{13}$$

Actually, this result is not approximate but a special case of an exact theorem due to Peterson [24].

Since higher than second order cumulants are zero for a gaussian system, the maximum entropy ansatz implies the response is exactly linear whenever the equilibrium J-fluctuations are gaussian. This is analogous to what happens in equilibrium statistical mechanics. A magnetic system, for instance, has a field independent susceptibility only if the free energy is quadratic in the magnetization. Note that nongaussian fluctuations survive in the thermodynamic limit, the central limit theorem notwithstanding. A simple example of this in statistical mechanics is energy fluctuations in the canonical ensemble. If the energy fluctuations are strictly gaussian, the average energy is linear in β so the specific heat varies as -2. Whenever this is not the case, the energy fluctuations are

nongaussian.

The maximum entropy formalism has a long history of applications to the problem of estimating the density matrix for a nonequilibrium system. This leads to a generalization of equilibrium statistical mechanics which takes into account the limited amount of information available about the system [25-29]. Some applications of the formalism characterize the non-equilibrium system by its energy dissipation rate [30,31]. As shown above, when applied to the external field induced "non-equilibrium" in the J(t)-space, this idea leads to definite predictions of the nonlinear response in terms of equilibrium fluctuations. The resulting ansatz Eq. (5) has been discussed briefly by Bochkov and Kuzovlev [13], referring to earlier work by Stratonovich [10]. Only the case $u(\tau)$=const. was considered and the discussion was limited to Markovian systems. No justification of the ansatz was given except that it satisfies the requirement of statistical mechanics Eq. (2). The maximum entropy property of the ansatz, on the other hand, shows that it is the most reasonable, given only a knowledge of the equilibrium fluctuations. This does not guaranty the ansatz is correct, however. To look into this question, we first discuss the consequences of a phenomenological Langevin equation for Q and then an exact result.

Suppose Q obeys a Langevin equation $\dot{Q} = C\,F(Q) + \xi(t)$ where $F(Q)=F_0(Q)+E$ is the generalized force and $\xi(t)$ is a gaussian white noise term. Then the path-probability is given by [32,33] $P[Q(t)] = N^{-1}\exp\{-\beta/(4C)\int_{-\infty}^{\infty}[\dot{Q}(t)-CF(Q(t))]^2 dt\}$, or

$$P_E[Q(t)] = N^{-1} P_0[Q(t)] \exp\left\{\beta/2 E\int_{-\infty}^{\infty} J(t)\,dt\right\} \exp\left\{-\beta/2 EC\int_{-\infty}^{\infty} F_0(Q(t))\,dt\right\}. \quad (14)$$

The transformation from $Q(t)$ to $\mathring{Q}(t)$ is linear. Therefore, Eq. (14) implies that the maximum entropy ansatz leads to correct results whenever the last term is unimportant. As an example, consider again a particle in one dimension in a periodic potential at low temperature. Because of the $P_0[Q(t)]$ factor, the important paths fluctuate for some time around a potential energy minimum before suddenly "jumping" to a new minimum. For these paths the last term of Eq. (14) is almost independent of the number of minima traversed and may be ignored for the calculation of $\langle \Delta Q(t) \rangle_E$ for large t. Thus, the maximum entropy ansatz leads to correct results in this case, as already shown in Eq. (9).

A result due to Furukawa sheds more light on the maximum entropy ansatz. He showed that, for slowly fluctuating $J(t)$, the exact microscopic equation of motion implies [34]

$$P_E[J(t)] = N^{-1} P_0[J(t)] \exp\left\{ \beta/2 \, E \int_{-\infty}^{\infty} J(t) dt + O(E^2) \right\}. \qquad (15)$$

Equation (15) shows that there are two different ways a system may become nonlinear: Either 1) as an interplay between nongaussian equilibrium J-fluctuations and the first order term, or 2) as a result of the higher order terms becoming important. The first case is when the maximum entropy ansatz gives correct results; this may be referred to as a "simple" nonlinearity since it results from the very same term in Eq. (15) that gives rise to the linear response. Upon increasing the external field, a system may pass from linear through simple nonlinear response to finally the "complex" non-linear response due to the higher order terms, or it may go directly from the linear to complex nonlinear response. The maximum entropy ansatz is never correct for the

latter systems, and in the former case it should only be trusted at not too large external fields.

To summarize, it has been shown that the maximum entropy formalism in conjunction with statistical mechanics leads to unique predictions for the external field cumulant averages of $J(t)$ in terms of equilibrium averages. The ansatz Eq. (3) may be justified in other ways. It corresponds to keeping only the first order term in Eq. (15) which is exact for slowly fluctuating $J(t)$. This term is responsible for the linear response, so the ansatz is clearly the simplest way to extrapolate linear response theory into the nonlinear regime. The extrapolation has the property that the response is exactly linear if the equilibrium J-fluctuations are gaussian. If Q obeys a Langevin equation, the ansatz is correct whenever the last term of Eq. (14) is unimportant; for slowly fluctuating $J(t)$ the requirement of consistency between Eqs. (14) and (15) implies that the extra terms of both equations must be insignificant and the maximum entropy ansatz must be correct.

The maximum entropy ansatz solves a conceptual problem, but open questions remain regarding the validity and the practical value of the ansatz. One obvious problem is that the ansatz predicts a universal form of the nonlinear response while one expects the response to depend on the way heat generated by the external field is removed. On the other hand, the ansatz only makes sense in situations where the temperature is almost constant throughout the sample (because the temperature enters into Eq. (5)). In bulk cases this requirement can be satisfied for a given external field by working with a sufficiently small sample; in this limit the problem of heating becomes insignificant. -- Equation (15) implies the ansatz can only be

valid at not too large external fields. Also, Eq. (15) implies that a system may become nonlinear either by first exhibiting the "simple" nonlinearity predicted by the ansatz before becoming "complex" nonlinear, or by going directly from the linear to the complex nonlinear regime. In this connection it should be noted that all formulas given above may be generalized to several degrees of freedom. One may speculate that, by including the "mode-coupling" terms to other relevant degrees of freedom, a complex nonlinearity may be converted to a simple, thus extending the validity of the ansatz. -- Even when the maximum entropy ansatz is valid, the practical value of it is not clear at present. It is possible that the calculation of the equilibrium higher order cumulant averages requires at least as much effort as a direct calculation of the nonlinear response. Certainly, this is the case for the above discussed simple random walk in one dimension. On the other hand, Eq. (12) has provided insight into the problem of 1/f noise in conductors. And, for instance, Eq. (10) gives explicit predictions for the response of a single atom to an external force, based on a knowledge of the equilibrium intermediate incoherent scattering function, a quantity which has been studied extensively [15].

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Vejleder: Per Nørgaard.

41/81 "PLANNING AND POLICY CONSIDERATIONS RELATED TO THE INTRODUCTION OF RENEWABLE ENERGY SOURCES INTO ENERGY SUPPLY SYSTEMS".
ENERGY SERIES NO. 3.
Af: Bent Sørensen.

42/81 "VIDENSKAB TEORI SAMFUND - En introduktion til materialistiske videnskabsopfattelser".
Af: Helge Kragh og Stig Andur Pedersen.

43/81 1."COMPARATIVE RISK ASSESSMENT OF TOTAL ENERGY SYSTEMS".
2."ADVANTAGES AND DISADVANTAGES OF DECENTRALIZATION".
ENERGY SERIES NO. 4.
Af: Bent Sørensen.

44/81 "HISTORISKE UNDERSØGELSER AF DE EKSPERIMENTELLE FORUDSÆTNINGER FOR RUTHERFORDS ATOMMODEL".
Projektrapport af: Niels Thor Nielsen.
Vejleder: Bent C. Jørgensen.

45/82 Er aldrig udkommet.

46/82 "EKSEMPLARISK UNDERVISNING OG FYSISK ERKENDESE-
1+11 ILLUSTRERET VED TO EKSEMPLER".
Projektrapport af: Torben O.Olsen, Lasse Rasmussen og Niels Dreyer Sørensen.
Vejleder: Bent C. Jørgensen.

47/82 "BARSEBÄCK OG DET VÆRST OFFICIELT-TÆNKELIGE UHELD".
ENERGY SERIES NO. 5.
Af: Bent Sørensen.

48/82 "EN UNDERSØGELSE AF MATEMATIKUNDERVISNINGEN PÅ ADGANGSKURSUS TIL KØBENHAVNS TEKNIKUM".
Projektrapport af: Lis Eilertzen, Jørgen Karrebæk, Troels Lange, Preben Nørregaard, Lissi Pedesen, Laust Rishøj, Lill Røn og Isac Showiki.
Vejleder: Mogens Niss.

49/82 "ANALYSE AF MULTISPEKTRALE SATELLITBILLEDER".
Projektrapport af: Preben Nørregaard.
Vejledere: Jørgen Larsen og Rasmus Ole Rasmussen.

50/82 "HERSLEV - MULIGHEDER FOR VEDVARENDE ENERGI I EN LANDSBY".
ENERGY SERIES NO. 6.
Rapport af: Bent Christensen, Bent Hove Jensen, Dennis B. Møller, Bjarne Laursen, Bjarne Lillethorup og Jacob Mørch Pedersen.
Vejleder: Bent Sørensen.

51/82 "HVAD KAN DER GØRES FOR AT AFHJÆLPE PIGERS BLOKERING OVERFOR MATEMATIK ?"
Projektrapport af: Lis Eilertzen, Lissi Pedersen, Lill Røn og Susanne Stender.

52/82 "DESUSPENSION OF SPLITTING ELLIPTIC SYMBOLS".
Af: Bernhelm Booss og Krzysztof Wojciechowski.

53/82 "THE CONSTITUTION OF SUBJECTS IN ENGINEERING EDUCATION".
Af: Arne Jacobsen og Stig Andur Pedersen.

54/82 "FUTURES RESEARCH" - A Philosophical Analysis of Its Subject-Matter and Methods.
Af: Stig Andur Pedersen og Johannes Witt-Hansen.

55/82 "MATEMATISKE MODELLER" - Litteratur på Roskilde Universitetsbibliotek.
En biografi.
Af: Else Høyrup.

Vedr. tekst nr. 55/82 se også tekst nr. 62/83.

56/82 "ÉN - TO - MANGE" -
En undersøgelse af matematisk økologi.
Projektrapport af: Troels Lange.
Vejleder: Anders Madsen.

57/83 "ASPECT EKSPERIMENTET"-
Skjulte variable i kvantemekanikken?
Projektrapport af: Tom Juul Andersen.
Vejleder: Peder Voetmann Christiansen.
Nr. 57 er udgået.

58/83 "MATEMATISKE VANDRINGER" - Modelbetragtninger over spredning af dyr mellem småbiotoper i agerlandet.
Projektrapport af: Per Hammershøj Jensen og Lene Vagn Rasmussen.
Vejleder: Jørgen Larsen.

59/83"THE METHODOLOGY OF ENERGY PLANNING".
ENERGY SERIES NO. 7.
Af: Bent Sørensen.

60/83 "MATEMATISK MODEKSPERTISE"- et eksempel.
Projektrapport af: Erik O. Gade, Jørgen Karrebæk og Preben Nørregaard.
Vejleder: Anders Madsen.

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: Berhelm 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 Yagn Rasmussen.
Vejleder: Klaus Grünbaum og Anders Hede Madsen.

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- et problem og en udfordring for skolen?
Af: Karin Beyer, Sussanne Blegaa, Birthe Olsen, Jette Reich og Mette Vedelsby.

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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.
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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.

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87/84 "A SIMPLE MODEL OF AC HOPPING CONDUCTIVITY IN DISORDERED SOLIDS".
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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.

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Projektrapport af: Biger Lundgren, Henning Sten Hansen og John Johansson.
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Af: Peder Voetmann Christiansen.

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Projektrapport af: Morten Blomhøj, Klavs Frisdahl og Frank M. Olsen.
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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.
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104/85 "ANALOGREGNEMASKINEN OG LORENZLIGNINGER".
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105/85 "THE FREQUENCY DEPENDENCE OF THE SPECIFIC HEAT AT THE GLASS TRANSITION".
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.

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Af: Bent Sørensen

111/85 JORDEN RUNDT PÅ FLADE KORT".
Projektrapport af: Birgit Andresen, Beatriz Quinones og Jimmy Staal.
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112/85 "VIDENSKABELIGGØRELSE AF DANSK TEKNOLOGISK INNOVATION FREM TIL 1950 - BELYST VED EKSEMPLER".
Projektrapport 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 II".
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.
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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