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In order to explore the existence of spontaneous self-organization of states in quantum optics on a more concrete basis and to learn from known examples of many-body systems that show self-organization, we have taken up the study of Heisenberg Ferromagnetism. This is the magnetism of spherically symmetric spins interacting via the exchange Hamiltonian on two or three dimensional lattices. We have extracted the essential elements necessary for self-locking and the ensuing metastability of the system in the absence of any external field. Since the functional space of the Heisenberg ferromagnetic spins is homomorphic to the space of two level atoms, our recent results in magnetism will allow us to pass with great ease to the Quantum Optics case of self-locked bistable states and demonstrate their existence on a first-principles basis.

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FINAL REPORT

on

A MICROSCOPIC THEORY OF QUANTUM OPTICS & NEW PHOTON-LOCKED BISTABLE STATES

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ABSTRACT:

In order to explore the existence of spontaneous self-organization of states in quantum optics on a more concrete basis and to learn from known examples of many-body systems that show self-organization, we have taken up the study of Heisenberg Ferromagnetism. This is the magnetism of spherically symmetric spins interacting via the exchange Hamiltonian on two or three dimensional lattices. We have extracted the essential elements necessary for self-locking and the ensuing metastability of the system in the absence of any external field. Since the functional space of the Heisenberg ferromagnetic spins is homomorphic to the space of two level atoms, our recent results in magnetism will allow us to pass with great ease to the Quantum Optics case of self-locked bistable states and demonstrate their existence on a first-principles basis.

General Discussion:

The central thrust of our research has been to derive the fully quantum mechanical dynamics of coupled many-body systems without resorting to Feynman type "perturbative" diagrammatic expansions. Rather, we wanted to approach the problem from the integral equations mode totally, by finding ways to reduce the problem to quadratures, making full use of the internal symmetry of the system as well as possible -- and because of it-- to use what we call "natural function spaces". We have found that in doing so the problem has indeed become tractable for the first time. Thus towards that goal we have made substantial progress that we shall outline below.

We were first able to do a static problem, namely the calculation of the electron energy levels of crystalline solids. This gave us a first-principles calculational theory for these levels which checked well with well known test cases and was very efficient in terms of computational time and convergence.

The next step was to use this approach for a case where dissipation was involved. We could have chosen a transport process in a crystalline solid with dissipation. However a much cleaner one would be an atomic system coupled to the infinite radiation bath, mainly because the Hamiltonian of, say, two level atoms coupled to the infinite mode radiation field is well known and unquestionable; thus results derived on this system, at zero temperature--and thus without thermodynamics-- would be indisputable; this would be particularly evident, since special cases had already been solved in quantum optics, although not from a single unifying microscopic theory --without invoking the mean-field approximation.

So we set out to solve the N-atom microscopic quantum optics problem, and we were able to derive most of the well known quantum results from our unified approach in one single theory. Thus we were able to describe superradiance, spontaneous emission, photon echo, and most significantly the dissipative process known as optical bistability.

This study we also led us to the discovery of new states which turned out to show very high stability; these states we called super-locked or self-locked states and then found out that there were analogs of these in magnetism.

We thus turned to magnetism not only because of these new findings but also because our initial goal was to carry out the full time evolution (dynamics) of coupled many-body systems and because the analytical result for the spin dynamics of one dimensional Ising system was already worked out by Glauber; thus we could check our results for this case first and then go to the more difficult Heisenberg ferromagnetism. The reason for insisting on doing the Heisenberg case rather than the Ising one is that the Heisenberg Hamiltonian is much closer to the true phenomenon of magnetism. An added bonus was that the Heisenberg system's functional space was isomorphic to that of the system of two-level atoms. Thus we would be able to carry out both finite temperature and real time dissipative dynamics of a coupled many-body system with our " statistical microdynamic" approach, being ever so truthful to the underlying dynamics of the Hamiltonian -- we believed!. Again, this was because we were going to make full use of the underlying "functional space" and not bring in any approximation whatsoever. In fact what we were going to do was a new form of calculation of the density matrix evolution where "coherent processes" were to evolve via the free evolutionary dynamics of the bath-free Hamiltonian via the quantum Liouvillian, but this process would be combined with statistically (thermostatistically) determined interruptions by the Bath; these "incoherent" interactions will shift the evolving state from its evolutionary path or "fiber" to a neighboring nearby path in the fiber bundle of states in the sense of a modified form of path integrals that include interruptive jumps in the paths.

We started with the full quantum dynamics of these spins but soon found out that this would limit us to the study of a very small number of spins because of the computational power (CPU time) required; we then discovered that we could already learn a lot from a kind of semi-classical -- but not a mean-field -- solution of the problem; thus we gravitated to that latter problem for the time being.

The results we got have been very remarkable and we have communicated these to our colleagues. Suffice it to say that new physics has emerged from these latter studies, and we are putting them to print as fast as is feasible. These computations are rather demanding in computer time -- and we are able to accomplish this feat by using a large cluster (10-20) of substations simultaneously in a powerful network environment-- thus essentially operating as if we have a supercomputer all to ourselves!

These results have been so interesting that our colleagues in elementary particle physics have learned from us and have embarked on application of the method to their field. We do already have results that shed light on a number of central key issues in physics, such as the role of ergodicity breaking and the superstable structures that we have been seeing lately, e.g. matastable alloys, the quasicrystals, the atomic clusters and their unusual magnetism, and finally a deeper understanding of phase transitions which can encompass fractal structures and chaotic time evolution on their way to a long range ordering.

Publications under the grant:

R. G. Brown and M. Ciftan," N-atom optical Bloch equations: A microscopic theory of Quantum Optics", *Phys. Rev.* **A40**, 3080 (1989).

R. G. Brown and M. Ciftan, " Multipolar integral equation theory and generalized multipole scattering theory", in Condensed Matter Theories **4**, p. 57; ed. Jaime Keller, Plenum Press, NY, 1989.

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R. G. Brown and M. Ciftan, " Quantum statistical microdynamics and critical phenomena, in Condensed Matter Theories **6**, p. 25, ed. Fantoni and Resati, Plenum Press (1991).

R. G. Brown and M. Ciftan, "The 2d-3D Heisenberg ferromagnet" in Computer Simulation Studies in Condensed Matter Physics, V, p.150, ed. D. P. Landau et.. al., Springer Verlag, NY (1992).

R. G. Brown and M. Ciftan, "Statistical microdynamics of extended systems in natural function spaces", to appear in *International Journal of Quantum Chemistry*, 1992.

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Brown and Ciftan, *Phys. Rev.* **B39**, 3543 (89)

A. K. Ciftci, R. G. Brown and M. Ciftan, Comment, Phys. Rev. B15 (1990).

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M. Ciftan, "Cluster Microdynamics", paper presented at the International Symposium on Local Order, Jeckyll Island, SC, June 1992.

Two papers are in preparation on the three-dimensional Heisenberg ferromagnet regarding its critical exponents and broken ergodicity in such systems, to be submitted to Physical Review Letters.

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