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II. Project Description

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1.1 Models of Nuclear Structure

In the last fifteen years the exploitation of symmetry ideas has led to major developments in nuclear physics as well as in other areas of physics. In particular, the introduction of the concept of dynamic symmetry, in which the energy operator does not commute with all the elements of a Lie algebra but is written instead in terms of invariant operators of its subalgebras, has led to the construction of realistic and yet solvable models of physical systems. The best example of these models is the interacting boson model[1] which was introduced in 1974 to describe properties of nuclei with collective quadrupole character. The model was subsequently expanded to include other degrees of freedom, such as octupole and hexadecupole degrees of freedom, as well as the degrees of freedom of individual particles which couple to the collective ones. The latter model, the interacting boson-fermion model[2], allows one to study the complex interweaving of bosonic and fermionic degrees of freedom which occurs in nuclei. The bosons here are the Cooper pairs, representing correlated two-proton and two-neutron states, while the fermions are the individual unpaired particles. The interacting boson model has been the subject of many investigations (the original articles have now been quoted more than 1800 times).

A part of our research program for the next three years will be the continuing exploitation of the interacting boson model, with particular emphasis to those aspects of collective states in nuclei which are being investigated experimentally at the present time. These aspects are:

(i) The study of high-spin states in nuclei ($J \geq 20\hbar$), especially in transitional nuclei where the use of other methods, such as the cranked Nilsson model, is inappropriate.

This study will be done in two different ways:

(a) For nuclei where the number of active pairs is not very large ($N \leq 10$), calculations can be done in the laboratory frame. The model space is divided into states with no broken pairs, with one broken pair, with two broken pairs, etc. The model Hamiltonian is diagonalized in this space and

energies and intensities of transitions obtained. This method has been used recently to compute properties of the Mercury nuclei up to spin $J \approx 30\hbar$ (two broken pairs)[3]. We plan to apply it to the study of other regions of the periodic table, such as the mass A~80 region (Zirconium) and A~130 region (light Samarium).

(b) For nuclei with a large number of active pairs and with one or more pairs out of the S-D condensate, the calculation in the laboratory frame becomes very cumbersome. For these nuclei, it is more convenient to do calculations in the intrinsic frame by constructing a classical version of the interacting boson-fermion model[4]. Calculations in the intrinsic frame can be done easily up to many broken pairs, since the matrices to diagonalize are rather small. The use of realistic boson Hamiltonians, as well as realistic boson-fermion interactions, together with the inclusion of couplings with the β and γ vibrations (shape fluctuations) make the classical version of the interacting boson-fermion model a better starting point for the analysis of experimental data than the Nilsson model which corresponds to a rigid, axially deformed situation. The intrinsic frame description of interacting boson-fermion Hamiltonians can then be cranked, allowing a very realistic description of high-spin states in deformed nuclei. A preliminary version of this method will appear soon[5]. We intend to exploit it in detail for the study of nuclei in the mass A~150 region, where many experimental data exist.

(ii) The study of the symmetry properties of states with very large quadrupole deformation (superdeformation), in particular whether or not Bose-Fermi symmetries and supersymmetries play a major role.

All possible symmetries of the collective quadrupole motion and its coupling to single particle states have been classified in Refs. 1 and 2. The problem here is to see to what extent the observed properties of superdeformed states, in particular of the "identical" bands recently discovered in several regions of the periodic table, can be described by one of the expected symmmetry types. In particular, in view of the axial deformation of the superdeformed states, the expected symmetries are of the SU(3) type (type II of Refs. 1 and 2). There are two possible levels of symmetry: (a) Bose-Fermi symmetries in which each individual nucleus is treated separately and (b) supersymmetries in which both even-even and even-odd (and odd-odd) nuclei are treated simultaneously. If the superdeformed bands have axial deformation, the associated Bose-Fermi symmetries are necessarily of the SU(3) type, as discussed extensively in Chapt. 3 of Ref. 2. It is however still not clear whether or not it is possible to arrange the observed bands into supersymmetric multiplets, similar to those observed in the low-lying states. We plan to investigate this point, as well as the fact that the observed states appear to display symmetries which are less broken (~0.1%) than those of the low-lying states (~10%).

1.2 Algebraic Models of Hadronic Structure

In addition to the above continuing study of nuclear properties, we have initiated another major research program in the area of hadronic spectroscopy. The idea here is to develop a model of hadronic spectroscopy, as complete and detailed as the interacting boson model of nuclear structure. The model is based on a string-like picture of hadrons, in which hadrons are depicted as quarks (and antiquarks) bound by strings[6]. By quantizing the strings excitations in terms of boson operators and the quarks (and antiquarks) in terms of fermion operators, one obtains again a system of interacting bosons and fermions. A preliminary analysis of meson states composed of a quark and antiquark ($q\bar{q}$) has given very encouraging results[7,8]. We intend to develop the model further by studying:

(i) Baryon states, composed of three quarks, qqq.

The major new technical problem which appears here is the construction of properly antizymmetrized states. This problem has been solved up to now only for harmonic oscillator wave functions, U(3) symmetry. The solution involves the embedding of U(3) into a larger algebra, Sp(12,R) as reviewed in Ref. 9. We plan to solve this problem in general for any wave function. In particular we intend to solve it for the O(4) symmetry, which, on the basis of the results obtained for ($q\bar{q}$) mesons, appears to be the appropriate symmetry of hadrons.

(ii) Multiquark configurations and their mixing with simple configurations, for example ($qq\bar{q}\bar{q}$) states and their mixing with ($q\bar{q}$) states.

The problem here is the development of a simple classification scheme of multiquark configurations (4,5,...-body problem) which will avoid the need for complex numerical calculations. We have already developed such a scheme for the four-body molecular problem, and plan to exploit it in the hadronic problem.

(iii) Gluonic configurations (glueballs) with two, three, or more gluons. While the study of states with quarks can be done by exploiting the techniques based on Lie algebras and their combinations, the study of gluonic configurations will require the use of more complex mathematical constructions, since in the string-like model, gluons are represented by continuous, closed strings. This will necessitate either the introduction of infinite products of Lie algebras or of infinite dimensional (Kac-Moody) algebras.

The hadronic project will be our main research program in the coming three years and its purpose is to have available a detailed analysis of hadronic properties at the time (~1994) when the new nuclear physics facilities devoted to the study of this problem will be in operation. We have here particularly in mind the CEBAF facility and its associated N^* program.

For details of the basic idea behind the hadronic project, see the attached preprint[10].

1.3 Reaction Theory

Beginning in the early 80's, we have started an investigation of the connection between scattering theory and group theory. We have found that a large class of S-matrices can be associated to certain properties of the orthogonal non-compact groups, SO(n,m). Among these, particularly important is the group of Coulomb scattering, SO(3,1). The discovery of this connection has open the way for a relatively simple parametrization of the multi-channel S-matrix for problems in which the Coulomb interaction plays an important role, in particular heavy ion scattering[11]. This parametrization has been used by several experimental groups to analyze heavy ion data. Analyses of up to 10 channels have been reported. A problem which has not been addressed in full as yet is the role played by the intrinsic spin. We intend to explore this role in detail in the coming years, since experimental data on scattering of heavy ions with spin begin to be available. This project is related to the structure projects in the sense that one can treat both the scattering and the structure aspect with algebraic methods, thus reducing the entire calculation to some algebraic manipulations. For heavy ion scattering, where the colliding ions are collective nuclei, the structure part can be treated by making use of the interacting boson model of Sect. 1.2.

An entirely new avenue is opened by the study of hadronic collisions in the few GeV range at the Saturne facility in Saclay, France and at the facility under construction in Jülich, Germany. We plan to use the model of hadronic structure of Sect. 1.2 to study elastic and inelastic collisions of hadrons in the few GeV range. This model will be combined with an S-matrix appropriate to hadronic scattering, in particular to the string-like aspect of hadronic interactions, as evidenced by the O(4) symmetry of the bound strings[7,8]. This project is complimentary to that described in Sect. 1.2, which remains our main goal.

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2. Y. Alhassid

2.1 Hot Rotating Nuclei

The possibility of heating up a nucleus to a finite temperature opens a new direction in nuclear structure studies. At high excitation energy the nuclear density of states is so high that it is practically impossible to resolve them. But when the complications increase beyond a certain point, the problem becomes tractable again since one is interested only in the average properties of the nucleus. Statistical methods become useful, although they should be applied with care because of the finite number (~100 for a heavy nucleus) of degrees of freedom.

Among the numerous phenomena encountered in the study of hot nuclei, phase-transitions are of particular interest. We have concentrated recently on shape transitions (T_c~1-3 MeV) in deformed nuclei, but many of the techniques that we are developing are useful in the description of other nuclear phase-transition phenomena. Recent advances in detector systems are making it possible to study properties of nuclei under extreme conditions of high excitation and high spin.

Recent work

I have developed a new macroscopic approach to hot nuclei[1], which is considerably simpler than various microscopic models, yet detailed enough to explain the observed data. It is based on the Landau theory of symmetry breaking phase-transition in statistical mechanics[2] and a macroscopic fluctuation theory of the order parameters. In the nuclear shape transitions, the quadrupole deformation parameters $\alpha_{2\mu}$ play the role of the order parameters[3]. A universal phase-diagram emerges in a reduced temperature-angular velocity plane. A transition from a collective prolate to a non-collective oblate configuration is predicted either as a function of temperature or spin[3,4].

Since the nuclear system is finite, fluctuations around the mean-field equilibrium configuration are important. Microscopically such fluctuations are accounted for in the finite-temperature RPA approximation. However this is not sufficient when some directions are "soft." We have developed a macroscopic approach to fluctuations in which uniform fluctuations in all five $\alpha_{2\mu}$ are treated exactly[5]. It should be noted that our theory is the first to include fluctuations not only in the intrinsic nuclear shape[6] but also in the nuclear orientation with respect to its rotation axis.

A major experimental probe of the shape and properties of hot nuclei is the giant dipole resonance (GDR) built on excited nuclear states. Finite temperature RPA[7] underestimates the resonance width and predicts that the width is almost insensitive to temperature, in contradiction with experiments. We have developed a macroscopic approach to the GDR based on the above fluctuation theory. Though several authors have recognized the importance of shape fluctuations[6], our theory is the first which is able to reproduce not only the observed spectral shape of the GDR but also the angular anisotropy of the GDR γ-rays emitted from the hot nucleus[8].

Non-adiabatic effects in hot nuclei require the introduction of time-dependent fluctuations[9]. In our macroscopic approach they are described by an equation of the Brownian motion type in which the free energy plays the role of an external potential and the random force is generated by the coupling of $\alpha_{2\mu}$ to all other degrees of freedom. A fluctuation-dissipation theorem determines the correlation function of this random force. When applied to the GDR, non-adiabaticity may cause motional narrowing[10] of the resonance, an effect that is also seen in condensed matter systems.

Proposed Research

Following recent experimental discoveries of superdeformation, we plan to explore the superdeformed configuration as a possible phase of the nucleus. This can be done by extending the current Landau theory to the sixth order in the combined power of deformation and angular velocity. We will find universal classes of phase-diagrams with phase transitions that include the superdeformed shape. While the transitions of the normal deformed shapes are mostly second-order, it seems that the transitions between the superdeformed and normal structures are first-order.

The study of electromagnetic properties of hot nuclei will continue to be an important part of this project. We shall extend our GDR studies to lighter nuclei (A~40) where isospin degrees of freedom should be taken into account. It is expected that the Coriolis coupling and orientation fluctuations will play a major role in this region in broadening the resonance with increasing spin. Recently, strong quasi-continuum E2 transitions were measured in transitional nuclei. Large fluctuations around the non-collective equilibrium configuration partially explain[11] these collective-like B(E2)'s. The existence of a superdeformed local minimum will cause an additional enhancement.

An important experimental issue is the feeding of normal and superdeformed configurations during the decay of the hot nucleus. A realistic decay scheme should include in addition to particle evaporation and electromagnetic transitions, a "hopping" mechanism[9] between various configurations in the nucleus phase-space. Our theory of time-dependent shape fluctuations provides such a mechanism. A related subject is that of dissipation at finite temperatures. We have shown that non-adiabatic effects in the GDR can be used to determine the dissipation of the collective motion. It is important to compare such dissipative parameters to those determined by other processes (such as hot fission) as well as to extract them from microscopic theories. Quantum dissipative tunneling (i.e. tunneling in the presence of coupling to other degrees of freedom) has been an active field of research in condensed matter physics in recent years. We intend to pursue this issue in the context of the decay of the superdeformed to normal deformed band.

It is known that the proton-neutron interaction plays an important role in low-lying collective nuclear states. Its importance at finite temperature can be investigated by constructing a Landau theory whose order parameters distinguish between neutron and proton deformation.

Several interesting general issues in our theory remain unresolved. In the treatment of fluctuations we have assumed that the shape parameters are classical. It is not clear what role is played by quantal fluctuations. They are certainly significant at low temperatures. The role played by higher order shape multipoles should also be investigated. Another issue is the significance of temperature fluctuations in the transformation from the canonical to the physical microcanonical ensemble.

An important quantity in both experimental and theoretical nuclear physics is the nuclear level density. It is surprising that the most commonly used expressions are still modified versions of the Bethe formula which are based on the mean-field approximation, while it is expected that the residual interaction may be responsible for significant corrections. Since the level density is the inverse Laplace transform of the nuclear partition function, we can use our finite-temperature methods to calculate level densities. Several years ago I developed[12] a new approximation to the nuclear partition function which takes into account fluctuations in collective variables. More recently our method was applied[13] to the quadrupole plus pairing Hamiltonian to predict a large enhancement of the level density with respect to the mean field level density. We have initiated an investigation of the effects of static fluctuations in all five quadrupole parameters $\alpha_{2\mu}$ on the level density at a given energy and spin. Our approximation methods for the partition function are particularly useful when the system is described by an algebraic model. After the algebraic models of hadrons discussed in Section 1.2 have been constructed, we intend to use them to calculate the partition function and equations of state of hadronic matter.

Our method for the study of the shape transition of hot nuclei can be used to attack other nuclear phase transitions such as the liquid-gas (T_c~7-12 MeV) transition above which the finite nucleus does not exist as such. This is achieved by implementing the correct order parameters which control the corresponding transition. The limiting stability of the compound nucleus, the role played by deformation in this stability, and the possibility of collective nuclear motion close to that limit are all interesting issues to be investigated.

On the experimental side it is expected that with the improvement of the present generation of experimental techniques it will become possible to control more accurately the nuclear phase space variables such as temperature, spin and isospin. This will allow a more detailed comparison with the theory.

2.2 Chaos in Nuclei

One way of dealing with the increasing complexity of the nuclear system at higher excitations is the statistical approach, where all states at a given energy are assumed to be equally probable. This approach, which was adopted in section 2.1, cannot provide information on finer details such as the level structure. Random matrix theory (RMT) is a different approach in which it is assumed that all laws of interactions are equally probable, except that they must be consistent with the fundamental symmetries of the system. These theories were useful thirty years ago in the study of fluctuation properties of neutron resonances in heavy nuclei. Their use was justified by the large number of degrees of freedom and the complexity of the nuclear compound. In recent years, however, a new understanding of RMT has emerged. It was conjectured that their validity can be extended to quantal systems with few degrees of freedom when the underlying classical motion is chaotic. In particular, the Gaussian Orthogonal ensemble (GOE) has been associated with chaotic systems with time-reversal symmetry[14]. This conjecture was confirmed in numerous studies of systems with two degrees of freedom.

The question which naturally arises is whether chaos could prevail in the low-lying collective part of the nuclear spectrum, where the number of relevant degrees of freedom is larger than two yet much smaller than that of the compound nucleus. Several studies have analyzed experimental data of such levels in various nuclei[14]. However in order to obtain good statistics it was necessary to combine levels belonging to different nuclear species and spin/parity classes, and therefore only partial conclusions could be reached.

The generic behaviour expected in the nucleus is mixed, i.e. intermediate between regular and chaotic dynamics. Our goal is to study the chaotic properties of nuclear states through the use of realistic theoretical models. With few exceptions, such as that of Rydberg atoms in strong magnetic fields, all of the model problems studied in the field of quantum chaos were unrealistic. A realistic description of collective nuclear dynamics requires at least five degrees of freedom (quadrupole). This larger number makes the study of chaos in real nuclei a much more challenging project.

The experiments planned for Gammasphere and Eurosphere will produce a wealth of information about multi-γ coincidence measurements. The correlations of these sequences of γ transitions can be connected to an intermediate statistics between the GOE (chaotic) and Poisson (regular). Thus while the so-called "complete spectroscopy" will probably not provide us with a detailed level scheme, we may learn about fluctuation properties of levels and intensities. This information is complementary to what statistical mechanics can tell us.

Recent work

I have recently initiated[15] an investigation of the chaotic properties of the interacting boson model (see section 1.1) which describes well the low-lying collective part of the nuclear spectrum for a large volume of nuclei. Our focus is the onset of chaos in collective nuclear dynamics. As an algebraic model, the above model has two important advantages for our study: (i) The number of states is finite and exact numerical solution (i.e. with no truncation errors) is feasible.
(ii) The completely integrable Hamiltonians of this model are relatively easy to identify as those which possess a dynamical symmetry. The Casimir invariants, in terms of which we express the Hamiltonian, form a set of constants of the motion in involution. There are three known dynamical symmetries: vibrational nuclei, rotational nuclei and γ-unstable nuclei.

In our initial study we considered the transition between rotational and γ-unstable nuclei. From the quantum-mechanical perspective we have studied both spectral and B(E2) intensity fluctuations. We constructed the nearest-neighbor level spacing distribution and the Δ_3 statistics of Dyson and Metha which measures spectral rigidity. The level statistics should be Poisson for a regular system and GOE for a chaotic system. Near the two dynamical symmetry limits the behavior is Poisson but in the intermediate regime we observe the onset of chaos.

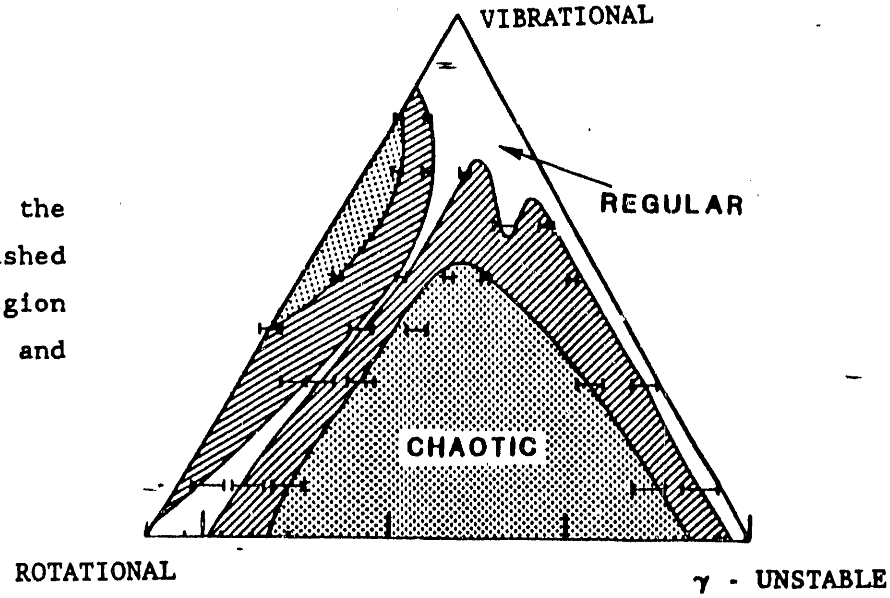
Several years ago I suggested[16] that transition intensities (which probe the wave functions) should be used as an additional measure of quantal chaos. In the GOE limit we expect to obtain the Porter-Thomas distribution. Deviations are measured in terms of χ^2 distribution in ν degrees of freedom. ν is 1 in the chaotic limit and decreases towards 0 for regular systems. We analyzed the B(E2) distributions in the interacting boson model and found strong correlations with the level statistics.

The "classical" limit is a mean-field dynamics obtained through the use of boson condensates. An interesting feature is that the inverse boson number plays the role of $\hbar$. Chaotic trajectories in the five collective quadrupole degrees of freedom are determined by their instability with respect to the initial conditions. Monte-Carlo methods are used to determine the fraction of chaotic volume on the energy-angular momentum surface and the Kolmogorov entropy. The classical analysis is important not only in correlating it with the quantal analysis but also in determining the onset of chaos as a function of excitation energy.

Proposed Research

We are in the process of generalizing the study described above to construct quantal and classical "chaotic" maps of the Casten triangle which describes the general family of interacting boson model Hamiltonians. The three vertices of the triangle are the three symmetry limits (vibrational, rotational and γ-unstable nuclei). The figure shows preliminary results of the classical chaotic map. An unexpected result seems to be a discovery of a new approximate symmetry which is associated with the regular strip connecting the rotational and vibrational vertices inside the triangle.

Chaotic map of the Casten triangle. The dashed area is the transition region between the regular and chaotic regions.



The role played by the proton-neutron interaction in the chaotic behavior of nuclei will be studied in the framework of interacting boson model-2 where neutrons and protons are distinguished from each other. Of particular importance is the appearance of a new quantum number, F-spin, which is the analog of isospin. It distinguishes between different symmetry classes under permutation of neutrons and protons. We will investigate the dependence of chaos on such symmetry. Magnetic M1 transitions have F-spin selection rules and their statistics will be analyzed.

To extend our analysis to higher spins and/or higher energies it is important to include in our model additional degrees of freedom such as broken pairs. For that purpose we shall use models discussed in section 1.1, where the Hilbert space includes in addition to the core, multi quasi-particle states. We plan to investigate the role played by the fermion-core interaction and the mixing interaction that breaks pairs, as well as Coriolis force effects on the dynamics. The "classical" limit will now show an interplay between the collective time-dependent dynamics and the motion of the quasi-particles in the deformed core. The study of such realistic models together with the planned multi-γ coincidence experiments should lead to a better understanding of chaotic phenomena in atomic nuclei.

Finally, it would be interesting to explore the signatures of chaos in the nuclear wave-function. Recent work in the field of quantum chaos led to the discovery of "scars" along unstable periodic orbits. We intend to follow a different approach by introducing entropy measures of the wave-functions with respect to the integrable limits. An operative criterion of chaoticity (or regularity) in the wave-function will provide the experimentalist with a tool for identifying "chaos" without the necessity of a "complete spectroscopy".

2.3 Reactions and Nuclear Structure

A statistical approach to nuclear reactions is feasible when the number of open channels is very large and they are not fully resolved. Several years ago we developed[17] a method which emerges from the generalization of a basic postulate of equilibrium statistical mechanics, that of entropy maximization, to non-equilibrium processes. The approach generalizes the phase-space approach of Fermi by constraining some dynamical observables.

When many channels are open but fully resolved, the traditional approach has been to solve the coupled channels equations. However, such an approach becomes increasingly difficult as the number of coupled channels increases. We have developed[18] algebraic models of scattering where the S-matrix is calculated by algebraic manipulations rather than by solving differential equations. In general it requires the use of non-compact groups. However, if the relative motion is treated semi-classically, I have shown[19] that the S-matrix becomes a representation matrix of the group which describes the composite target. The S-matrix is then effectively solved to all orders in the interaction without solving the coupled channel equations. Recently this idea has been used in the framework of the Glauber approximation to solve the inelastic scattering of medium energy (~800 MeV) protons from heavy nuclei[20], as well as electron-molecule scattering[21]. We are generalizing the approach to include interactions that are non-linear in the algebra's generators. The algebraic-eikonal approach breaks down at lower collision energies and at backward angles. It is then possible to develop an algebraic approach based on a generalization of the rotating frame approximation[22], in which the multi-channel problem is reduced to a collection of one-body scattering problems. This approach does not assume the eikonal limit. We are planning to apply it to proton and alpha scattering from heavy nuclei at energies (~20-100 MeV) where the eikonal limit is inapplicable. These methods are particularly useful for transitional nuclei which are difficult to describe in the traditional approach.

For possible applications to hadronic collisions see section 1.3.

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3. D. Kusnezov

3.1 Hadronic Spectroscopy

We have begun a detailed investigation into the properties of excited hadrons, in support of the proposed research of the N^* collaboration at CEBAF (see section 1.2). By considering hadrons in a string-like picture, one can study the excitations of the flux tube[1]. The algebra that describes the quantized bosons of the string excitations, together with the algebras for the internal degrees of freedom of flavor, spin and color, form a spectrum generating algebra (SGA). The result is an algebraic framework which is not committed to any particular relativistic or non-relativistic formalism, and which is sufficiently simple to yield analytic results. We have recently analyzed the $q\bar{q}$ component of mesons using this approach. One of the novelties here is that we are able to compute decay widths in closed form, including the finite size effects of the hadron[2]. We obtain results of comparable quality to those of non-relativistic and semi-relativistic quark model calculations. Another striking feature is our ability to obtain power law form factors for mesons. Presently we have investigated $q\bar{q}$ excitations and their photo-deexcitations and strong decays[3]. The framework is sufficiently general to include higher order contributions such as $q\bar{q}q\bar{q}$ and higher excitations. In the near future we plan to begin detailed studies of qqq baryons and eventually higher order contributions in baryons.

3.2 Signatures of the Quark-Gluon Plasma

The current ultra-relativistic heavy ion experiments at CERN and the next generation of experiments to be performed at RHIC will focus on signatures of a quark-gluon plasma (QGP). One of the promising observables are transverse momentum distributions. If there is local equilibration, this observable measures directly the pressure of the hot hadronic matter or of the quark-gluon plasma. On the empirical side, the data from CERN has shown some very puzzling features that point to a nontrivial behavior of hot matter. These include (a) an excess of soft photons and (b) a two-component transverse momentum distribution of final state pions. The pion spectrum appears to be the sum of two exponentials, each with a slope characterized by 1/T, where T is the temperature. At low tranverse momentum, the spectrum has a steep slope suggesting a low T component, while at higher $p_\perp$, the spectrum has a smaller slope, indicating a higher T component. I have been investigating the transverse momentum distribution of final state pions, known as the soft pion puzzle[4], which is very suggestive of a cooled phase of matter. This cool component in the spectrum accounts for roughly 25% of the final state pions[5]. It is important to consider whether hadronic scenarios can be used to account for this cool phase, rather than resorting to quark-gluon plasma arguments. Using a hadronic scenario, I have investigated several possibilities. After the collision, the system will cool as it expands. In contradiction to recent phenomenological explanations, our relativistic covariant treatment of the collective pion flow results in a transverse momentum spectrum which appears to have a low $p_\perp$ suppression, rather than the experimentally observed enhancement[6]. A reasonable question to ask is whether the soft pion enhancement is due to the decay of resonances. In a detailed analysis, meson and baryon resonances have been included and their subsequent decay into low momentum pions studied[7]. We have used extreme statistical models for initial hadronic abundances, from chemical equilibrium, to assigning statistical weights according to the spin and isospin degeneracies, as suggested by string breaking pictures. In all these cases, resonance production does not seem to be an important factor at CERN energies. However, we have found that it is possible to account for a small amount of enhancement from the decay of fat flux tubes. In CERN heavy ion collisions, flux tubes are formed as the nuclei pass through each other. When these tubes are sufficiently dense, they can coalesce to form multiquark flux tubes. These fat flux tubes can be shown to produce a softer pion spectrum[8]. Unfortunately, the characteristic temperature of the radiated pions depends too weakly on the size of the flux tube to account completely for the effect. As a result, simple explanations of the experimental situation using hadronic matter have not yet been able to account for the soft pion puzzle. I plan to continue my investigation of the nature of the QGP and its signatures.

3.3 Octupole Collectivity in Nuclei

The question of whether or not stable octupole deformation is realized in nuclei has been the source of recent experimental investigations in nuclear structure physics. Such nuclei were found in both the neutron-rich rare-earth and light actinides.

We have recently constructed[9] an extension of the interacting boson model (see Section 1.1) which includes the octupole degrees of freedom. While nuclei with large quadrupole deformation are usually described by the algebra SU(3), the situation is more complex when octupole and quadrupole deformations are considered simultaneously. We found that in the latter case there are at most six interesting dynamical symmetries[9]. Each of these limits has been explicitly constructed[10]. It remains to examine the characteristic structure of these limits to see which of them are realized in nuclei.

On the phenomenological level, we found that almost all the experimental signatures of octupole deformation can be explained in terms of octupole vibrations. This suggests that octupole deformation does not seem necessary in the rare-earth region. Our calculations have also been extended to more complex situations, such as the structure of ^{96}Zr. We find that there is an octupole two-phonon quartet of states, which is strongly mixed with the ground state and two-particle four-hole intruder configurations. This mixing strongly fragments the E1 strength, obfuscating the double octupole character of the multiplet. As a result, E3 transitions from the double octupole states are suppressed and hence cannot be used as a guide to the presence of these states[11].

3.4 Finite-Temperature Methods For the Many-Body Problem

We are developing quantitatively new methods to model equilibrium and non-equilibrium phenomena at finite temperature for both classical and quantum systems[12-14]. Our goal is to use these techniques to calculate statistical properties of many-body systems in general, and of nuclei in particular. These methods are nontrivial generalizations of molecular dynamics (MD). MD methods have certain advantages over such approaches as Monte-Carlo and Langevin-type equations and they proved to be extremely efficient even in lattice gauge simulation. In our methods, the classical equations of motion are modified in a simple way by adding pseudo-friction coefficients, which fluctuate in time so as to mock the coupling to a thermal bath. The equations of motion of the extended system can be made completely ergodic, and the canonical ensemble average is replaced by a simple time average over the trajectory. Previous approaches often failed to display ergodicity and consequently did not lead to reliable computational schemes. We have shown in test cases that our improved version produces ergodic trajectories and in most cases converges faster. When a canonical set of coordinates is known, the theory can be applied directly[16]. In other cases, such as algebraic Hamiltonians and constrained dynamical systems, non-trivial topologies may occur, where canonical coordinates cannot be globally defined. Even in these cases, our methods can be applied. We intend to investigate the temperature dependence of the specific heat of hot nuclei in this way.

We plan to develop a quantum version of MD methods for computing canonical ensemble averages. There are several possibilities at the moment. The simplest one is to use a path integral formulation of the quantum problem. Another possibility we are considering consists in "quantizing" the pseudo-friction coefficients. We will then be able to apply such methods to address nuclear problems at finite temperature. For example, we will compute the nuclear partition function of the quadrupole plus pairing Hamiltonian.

An important part of our project is the ability to model non-equilibrium processes as well. We have recently modeled[14] Brownian motion in this way, using deterministic and time-reversal invariant equations of motion, rather than the usual stochastic Langevin treatment. It is remarkable that a diffusion process can be described without any recourse to dissipation (time irreversibility) and/or random noise (non-deterministic element).

To test our techniques we are studying a lattice spin model, the XY model. This provides a good testing ground, since its properties near the phase transition have been studied in detail in the past. We have investigated 16 x 16 and 64 x 64 lattices on a CRAY-YMP computer and we have compared our results to standard and "improved" hybrid Monte Carlo calculations[15]. Our preliminary results indicate that we have smaller critical exponents and

prefactors near the phase transition. Since our mthods are based on MD, they can also be easily generalized to systems involving fermions.

3.5 Classical Limit Of Algebraic Hamiltonians

The classical limit of a system described by an algebraic Hamiltonian is useful for the geometrical interpretation of the model and for the study of its chaotic properties (see Section 2.2).

We have developed[17] a framework which defines the classical limit in terms of the generators of the Lie algebra, rather than in terms of canonical coordinates and momenta. We find that topology plays animportant role in the classical dynamics and in its requantization. In particular, gauge fields define the structure of the classical action for the Lie algebra. Their significance was demonstrated in a recent application to an effective Hamiltonian describing collective nuclear motion[18].

When the generators of the quantal Lie algebra are replaced by c-numbers, we obtain the classical phase space with its symplectic structure given in terms of the structure constants, as is also discussed in Ref. 19. There are certain conceptual differences between our approach and other approaches[20,21]. In our opinion, the direction followed in Refs. 17 and 18 is more suitable for the purposes of large amplitude collective motion. We also plan to examine the classical limit of algebraic nuclear hamiltonians, which are ideally suited to address the question of classical chaos and its connection to quantum phenomena.

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