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Scientific interests & program for the future

SCIENTIFIC INTERESTS

Hadron Physics: Phenomenology in vacuum and at nonzero temperature and density

The by far dominant contribution (95%) to the visible mass of the universe stems from the nonlinear dynamics of QCD. This crucial phenomenon arises from the so-called trace anomaly (dilatation symmetry and its explicit breaking at the quantum level) and from the spontaneous breaking of chiral symmetry ('Mexican-hat' form of the potential). The development of a low-energy chiral model based on both mentioned properties (dilatation and chiral symmetry together with their breaking) has been in the center of recent efforts in my group at the Uni Frankfurt, also involving Bachelor, Master and Ph.D. students.

The meson sector of the model, called extended linear sigma model, contains the usual pseudoscalar and scalar quark-antiquark mesons, but also the vector and axial-vector mesons, and in addition, a dilaton/glueball field. The aim is a as far as possible complete model with all relevant mesonic degrees of freedom up to 1.7 GeV. Quite remarkably, the inclusions of (axial-)vector fields has a very strong effects on the overall phenomenology, including the (pseudo-)scalar sector as well. For this reason the results obtained with this approach differ substantially from older hadronic models. Moreover, as recent publications of our group have shown, a very good agreement of the theoretical predictions with the experimental results listed in the Particle Data Group was obtained. Thus, one can conclude that a consistent investigation of hadron properties can be achieved with the inclusion of (axial-)vector fields.

Within our theoretical scheme we can also investigate the enigmatic nature of light scalar mesons. The (predominantly) quark-antiquark states are found too be quite heavy: the chiral partner of the pion is the resonance $f_0(1370)$ (and not the lightest scalar state $f_0(500)$). In our approach we also couple the glueball from the very beginning to the other mesons and we can then study it and its mixing with other states a chiral framework: according to present results, the resonance $f_0(1500)$ has the largest gluonic amount. It should be stressed that a full understanding of scalar states, together with the identification of the scalar chiral partner of the pion, is not only important for vacuum's spectroscopy, but is also crucial at nonzero temperatures and densities, in which the condensates decrease and symmetries are restored.

A recent result was the inclusion of the lightest pseudoscalar glueball with a lattice-predicted mass of about 2.6 GeV. The branching ratios are parameter free predictions which can be tested at BESIII experiment and, in the future, by the PANDA experiment at FAIR in Darmstadt.

The outlined theoretical approach was also put forward in the baryonic sector. A central issue is the mass of the nucleon, which is one of the basic building blocks of matter and the by far predominant origin of the mass of macroscopic bodies. The role of the chiral (quark-antiquark) condensate, as well as the roles of the gluon and tetraquark condensates, is investigated. The result of this study shows that a significant interplay of these quantities takes place in the process of the formation of the mass of the nucleon.

In all the aforementioned projects a basic tool for the study of phenomenology is the calculation of strong, electromagnetic and weak decays of hadrons. Decays are ubiquitous in particle physics and represent a fundamental connection between theory and experiment and between hadron physics and other processes of the Standard Model. Beyond these important practical properties, a deeper study of decays of particles in Quantum Field theory represents an exiting research project on its own, see the next point.

Many interesting outlooks of the chiral model exist, which shall be discussed in the ‘program for future research’.

Decays in Quantum Mechanics and Quantum Field Theory

Unstable particles are ubiquitous in Physics, but the time scale for decays can vary of many order of magnitudes: particles which decay through the strong interaction have a mean life time of about 10^{-20} sec, while some weak decaying nuclei can live thousands of years. A precise theoretical framework to describe decays, which goes beyond the standard formulae, is therefore important both in Quantum Field Theory and Quantum Mechanics.

The decay law is not an exact exponential, but deviations are present in both the short- and the long-time regimes. Indeed, short-time deviations from the exponential law were already confirmed experimentally with the use of cold atoms. The detailed theoretical understanding of these deviations and the search for other physical systems which display them is an interesting and fascinating subject linking many areas of Physics, such as quantum computing, quantum optic, and fundaments of Quantum Mechanics. New results in this direction can have also far-reaching consequence for applications.

My main interest has been the investigation of the non-exponential decay law in Quantum Field Theory. Namely, Quantum Field Theory is the theoretical framework which describes the creation and annihilation of particles, and thus is relevant to understand the decay of unstable particles. It is possible to show that the non-exponential decay law holds also in a genuine relativistic quantum field theoretical approach. For instance, large deviations take place for short-living unstable hadrons, but the study can be extended to other elementary and/or composite particles.

The case in which an unstable particle decays in two (or more) decay channels is also extremely interesting because new phenomena arise. The branching ratio is not a constant as function of time (the ratio of the partial decay widths), but shows sizable deviations from it, which can persist also for a long time.

Quantum field Theories at nonzero temeprature

Studies of field theories at nonzero temperature represents an important area of research, which allows to investigate the thermal properties of phenomenological models –such as the one previously described- and compare it to ongoing experimental activity and lattice simulations. At the same time, a better understanding of thermal field theories is also relevant for the fundaments of Quantum Field Theory.

In the chiral group of Frankfurt O(N) models at nonzero temperature were studied: in particular, the use of polar coordinates, instead of the usual Cartesian ones, and a new approach which makes use of the auxiliary field method were recently investigated. The aim is to study the order and the properties of the chiral phase transition and to investigate the symmetry of the system in presence of temperature and chemical potential.

Another interesting area of research, on which I actively worked, is the investigation of Yang-Mills at nonzero temperature. Indeed, Yang-Mills theories constitute the basic mathematical structure of the Standard Model. Although the field equations are nonlinear, the high degree of symmetry allowed finding nonperturbative solutions to the equation of motion, called instantons, and their generalization to nonzero temperature, called calorons. The study of the thermodynamical properties of Yang-Mills theory is then fundamental for many present issues in theoretical physics: QCD, Weak-gauge sector, and possible extensions of the Standard Model.

Further study of nonperturbative physics using low-dimensional models with nontrivial topology were recently undertaken by me and collaborators: The so-called O(3) model in 1+1 dimensions shows many of the interesting features of Yang-Mills theory: trace anomaly, asymptotic freedom, and instantons. We have performed a lattice and analytical study of this system, finding a good and parameter-free agreement between the two methods. The final aim is to improve in a controllable way our techniques dealing with nonperturbative physics at nonzero temperature.

Cosmology

In the very early and the very late stages of the life of the universe an inflation phase is (most probably) realized. The original, primordial inflation caused a fast expansion of the universe. It is however a puzzling feature that the present, late stage, inflation rate is very weak and started only ‘recently’ to dominate. This is puzzling because basic considerations of Quantum Field Theory lead to the prediction of a very large cosmological constant (the so-called cosmological constant problem).

A possible solution of this problem, on which I worked, consists in postulating the existence at the origin of the universe of many chiral fermions. A breaking of chiral symmetry generates an inflation phase, which is after a short phase relaxed to (almost) zero. Indeed, a further very light Goldstone field emerges out of this phenomenon and plays nowadays the role of a quintaxion field, being responsible of the present slow acceleration. In this way a possibility to combine these two, otherwise disconnected, aspects of the evolution of the Universe can be achieved.

PROGRAM FOR FUTURE RESEARCH

Future research will focus on the scientific interests outlined above. The aim is a close interrelation of theoretical developments with present experimental activity. In particular, the following research projects are planned for the near future:

Hadron physics in vacuum and in the medium

The finalization of the development of a model for hadrons which offers a satisfactory description of the reach and complex vacuum's phenomenology of mesons and baryons is necessary. Moreover, its application to nonzero temperature and density shall be investigated: this is relevant for heavy ion experiments and also for the understanding of neutron stars and the early phase of the universe. The details, and which processes can be studied, are described in the following:

- Applications of the model toward the study of experimentally relevant processes in the vacuum. In the mesonic sector future studies shall include: (i) The weak gauge bosons, which are relevant in the study of the decay of the tau lepton into hadrons; this is an important process to investigate the spectral functions of vector and axial-vector mesons. (ii) Inclusion of mesons containing the charm quark, thus enlarging the symmetry group to SU(4). Although the large mass of the charm represents a strong explicit breaking of chiral symmetry, the interactions still fulfill it; it is then possible to study the masses and decays of charmed mesons within a chiral framework. (iii) The inclusion of the Wess-Zumino anomalous term(s) allows to study a variety of processes which are currently investigated in many hadronic experiments. (iv) Breaking of isospin symmetry by taking into account the mass difference of the quarks u and d. This project enables to reach a higher precision and is relevant in selected processes. (v) Other meson nonets, such as the pseudo-vector mesons and their mixing with axial-vector mesons, can be included.
- In the baryonic sector the following studies are planned: (i) Inclusion of strangeness. This is an important step which allows to describe all relevant low-lying baryons and their masses and decays. (ii) Enlarged mixing scenarios, in which both the nucleon and the Roper resonances are included from the very beginning. (iii) Study of nucleon-(anti)nucleon scattering; relevant processes in which in the final states mesons (such as the eta and omega mesons) are emitted shall be studied in detail. Within this context one can also study the dilepton production in nucleon-nucleon scattering.
- Applications of the approach toward the study of the phase diagram of QCD at nonzero temperature and at nonzero density. The role of additional meson states, such as tetraquarks or molecular states and glueball, shall be investigated. The behaviour of masses and condensates as function of temperature and density will be an important outcome of this project. When going to large temperature and densities also the following issues need to be taken into account: the emergence of quark and gluonic degrees of freedom; this can be achieved by coupling the hadronic degrees of freedom to the quark currents and making use of the Polyakov loop: in this way a complete quark-based sigma model can be written down. At nonzero density and moderate temperature the possible existence of the quarkyonic phase and the emergence of inhomogeneous condensates need to be addressed.
- A model which is phenomenologically consistent in the vacuum can be used to study neutron stars. The aim of this project is to have a single approach to treat hadronic processes measured in experiments and astrophysical data on compact objects.
- In the first stage of the universe the deconfinement/confinement and the chiral phase transitions have taken place. An interesting outlook consists in evaluating within the

developed chiral approach the inflationary phase driven by the spontaneous breaking of chiral symmetry when the universe expands.

Quantum Mechanics and Quantum Field Theory: decay law and fundaments

Quantum Mechanics and Quantum Field Theory represent the basis of our fundamental understanding of Nature. Yet, profound questions about the fundaments of these theories can be addressed, especially in relation to the study of unstable particles. This subject allows connecting different areas of Physics. We summarize some main points for future studies:

- Description of unstable states in Quantum field Theory: mathematical objects such as poles in the second Riemann sheet, spectral functions and branch cuts needs to be addressed. The results can be applied to standard model processes: besides the spectral functions of hadrons, one can also study such properties for the Higgs boson and the weak gauge bosons. Namely, the description of the spectral functions of Standard Model particles, and the validity of the so-called Källen-Lehmann representation, is an interesting and not yet solved subject in Quantum Field Theory.
- Deep understanding of the decay law. Deviations from the exponential law for both slow and fast decay processes are now established in Quantum Mechanics, but can and should be also studied in Quantum Field Theory. While interesting results were already obtained (see scientific interests, the decay in Quantum Mechanics and Quantum Field Theory), the detailed study of all possible classes of Quantum Field Theories (superrenormalizable, renormalizable and non-renormalizable) represents a task for the future. The case of many decay channels needs to be further studied in order to make contact with specific examples from particle phenomenology and in order to understand better its mathematical properties.
- Development of a theoretical approach in which the measurement is taken into account in the study of decay processes. The aim is a quantitative study of the influence of the measurement process on the decay law. Namely, an interesting idea is that the properties of a decaying particle are affected by the way we measure it. In this context it is also possible to study foundational issues of Quantum Mechanics, which deliver falsifiable predictions such as the quantum Zeno and anti-Zeno effects.