BOSONIC VARIABLES IN NUCLEAR MATTER

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Abstract

It is shown that the boson theoretical interpretation of nuclear forces nessecitates the introduction of bosonic variables within the state function of nuclear matter. In this framework the 2-boson exchange plays a decisive role and calls for the introduction of special selfenergy diagrams. This generalized scheme is discussed with the help of a solvable field theoretical model.

1. Introduction

Microscopic nuclear theory was in a first attempt based on phenomenological two-body potentials which were determined from a detailed comparison with the empirical nucleon-nucleon scattering phases. These potentials are given by special analytical expressions which contain a large number of parameters adapted to the experimental data[1]. These expressions are then taken over - without any change - into the well-known approximation schemes for nuclear matter. In an earlier stage the two different methods, i.e. the Brueckner theory and the variational methods (in particular the Fermi Hypernetted Chain Approximation) were in characteristic disagreement, but the introduction of higher terms in Brueckner's approximation led to a satisfactory agreement between the two theoretical schemes[2,3]. Having thus reached some confidence with respect to these approximation schemes it turned out, however, that all results based on phenomenological potentials were in disagreement with empirical values. (In the case of the well--known Reid-potential the density is too high and there is also a slight overbinding). The situation appears to be unsatisfactory also from more general viewpoints: It turns out that various phase equivalent but different phenomenological potentials inserted in the same approximation scheme for nuclear matter may produce results which differ in an essential way. This means that the properties of nuclear matter yield an interesting test for different explicit expressions for nuclear forces. Unfortunately, all these theoretical results disagree with the experiment, i.e. they lie outside the empirical point in the well-known density binding diagram (so-called Coester-line, compare Fig. 1). It thus appears to be impossible to make a definite choice among the different phenomenological potentials. Apart from the fact that these potentials are determined by large numbers (up to 4o) of unphysical parameters, it thus turns out that this phenomenological approach leads to a characteristic contradiction between the free nucleon-nucleon scattering (which determines the parameters) and the properties of nuclear matter.

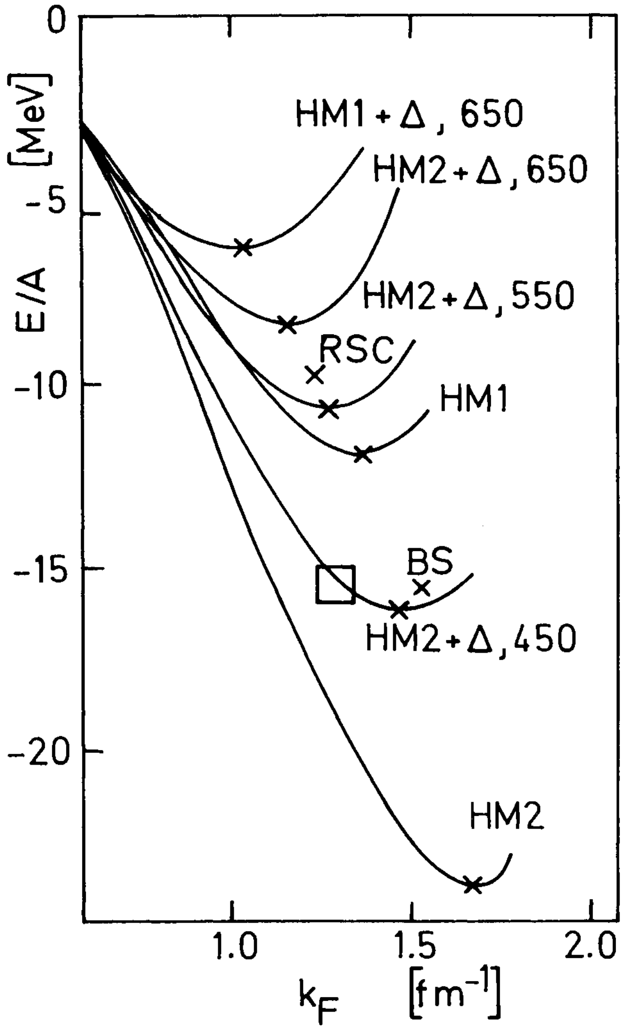

Fig. 1 Nuclear matter binding energy per particle E/A as function of the Fermi momentum k_F. The solid curves show the results for different "Bonn potentials" with and without intermediate Δ-isobars and for different cut-off masses Λ (in MeV) for the transition potentials. The saturation points (crosses) do not leave the Coester-line. The crosses at RSC and BS give the saturation points obtained with the Reid soft--core and the Bryan-Scott potentials and the box presents the empirical result.

2. The One Boson Exchange Potential

This situation will by now be improved step by step with the help of the boson theoretical viewpoint, in particular with the help of the introduction of bosonic variables within the structure of nuclear matter. In the framework of a first step, the so-called One-Boson-Exchange-Potential (OBEP) has to be discussed[4]: The exchange of a sequence of experimentally known bosons is treated with help of the so-called ladder approximation (Lippmann--Schwinger equation). The corresponding coupling constants and the rather important form factors of the boson-nucleon vertices are partly determined through a comparison with the empirical scattering phases. In the framework of this approximation it was, however, of capital importance to replace all 2-pion (more generally 2-boson) exchange terms which, as we will see, play a rather important role in the middle range part of the potential by the introduction of the unphysical σ-boson which, in turn, is treated again through the simple ladder approximation. The corresponding mass, coupling constant and form factor are for the moment treated parameters to be fitted to the experimental data. In spite of all these strong simplifications it turned out that this scheme is rather successful: The empirical phase shifts are perfectly reproduced with the help of a relatively limited number of parameters (coupling constants and form factors) which are - as far as they are directly measurable - in reasonable agreement with values obtained from particle physics. A great advantage with respect to the various phenomenological potentials, mentioned above, is a certain unicity and the fact that the parameters to be adapted are very much reduced in number and have to some extent a physical meaning. At the same time, this meson theoretical expression of the nucleon-nucleon potential yields a natural interpretation of the various terms: : The long-range tail is determined through pion exchange, the middle range attractive part, which plays a decisive role in nuclear matter, comes from the σ-boson and the repulsive core is due to the exchange of the vector bosons ω and ρ In spite of this success it turns out, however, that the insertion of this boson theoretical expression into the approximation schemes for nuclear matter yields nearly the former result with its characteristic disagreement: The density appears to be too high and the binding too large. (These values correspond, in fact, more or less to the results from the phenomenological Reid-potential).

3. Bosonic Variables

In view of this failure it is of decisive importance to observe that the boson theoretical viewpoint leads in a natural way to an understanding of this problem: If our potential is determined from a boson theory, it is clear that the effect of the boson exchange depends - via the Pauli principle - on the surrounding of the nucleons in question. In other words, the interaction between two nucleons embedded into nuclear matter differs in a characteristic way from the one between free nucleons. In order to obtain a handle on this effect, a natural enlargement of the description of nuclear matter is needed: The state function has to contain not only the variables of the nucleons but also the occupation number of the various boson states. In other words, the bosonic variables have to be introduced explicitly. This leads to the problem of treating the following field theoretical Hamiltonian: $H = H_o+H_1$ where H_o is the Hamiltonian of the free (nonrelativistic) nucleons and (the relativistic) bosons (treated both as quantized fields) and H_1 describes the interaction between the nucleon and the various boson fields (containing thus all the parameters of the various vertices which are again determined from an adjustment to the scattering problem). It has now been shown by D. Schütte[5] that this Hamiltonian may be used in the framework of a generalized Brueckner theory (roughly speaking, this amounts to replace within the hole-line expansion the lines which correspond to the potential by the various boson lines and to change the characteristic denominators). This procedure leads automatically to the enlarged state function, mentioned above. In a first step this scheme - including the same bosons as before - is again applied to nuclear matter: In spite of relative important changes within the calculation the old discrepancy remains: The result is again a point on the "Coester-line", i.e. in disagreement with the experimental values. On the other hand, the new state function yields a clear indication about the origin of this problem. The unphysical σ-boson which so far was still included in this analysis plays by far the most important role within this comprehensive state: The corresponding amplitudes exceed the ones of the other bosons by an enormous factor (comp.Fig.2). One might thus say that nuclear binding is due to a large extent just to the "formal" σ-exchange. This fact strongly suggests to introduce the 2-pion exchange explicitly, i.e. to replace this hypothetical σ-exchange through the underlying physical processes. In order to do so in a systematic way, it is of great importance to use the bosonic variables explicitly. (The introduction of these additional variables is needed anyhow in a systematic treatment of the so-called meson currents as well as in an explicit representation of the boson condensation).

4. The 2-Boson Exchange

In the framework of this program it is, first of all, of greatest interest to calculate the nucleon-nucleon scattering through this detailed description of the 2-pion exchange[6]. (It is in this connection of some importance not to use the well--known method of dispersion theory because it will be seen that this detailed determination leads to the strong and characteristic changes of the binding energies which otherwise would be lost).This program amounts to treat explicitly a large

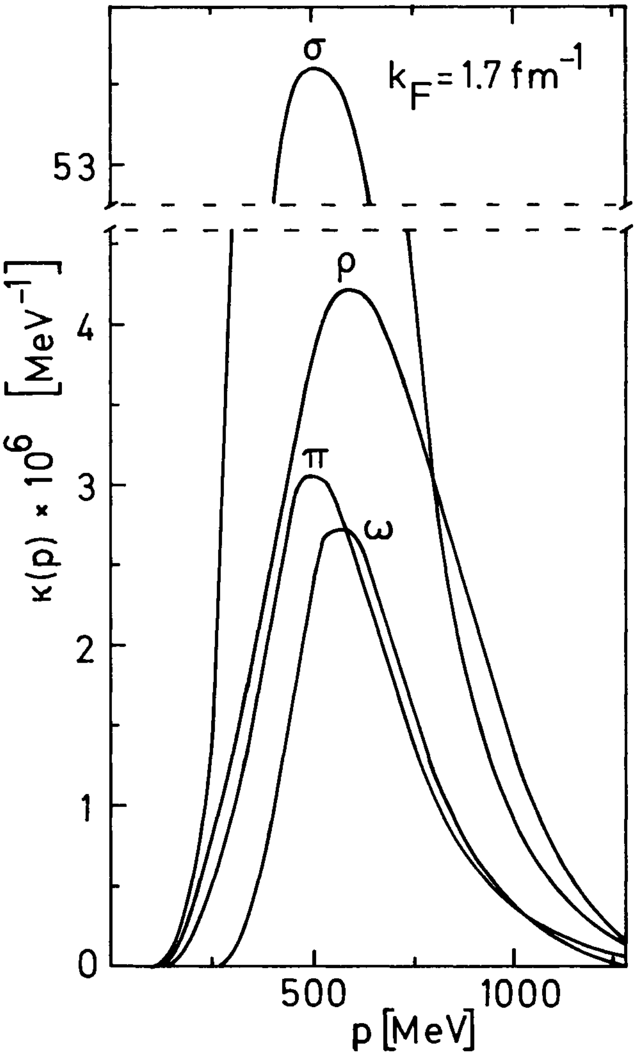

Fig.2 Probability distribution $\kappa(p)$ for different mesons of the standard OBE-scheme in nuclear matter as function of the mesonic momentum. $k_F = 1.7\ fm^{-1}$ is the saturation density obtained with the non-covariant "Bonn potential" without box diagrams which was used for this calculation. From "The mesonic degrees of freedom and nuclear wave function" W. Ferchländer, K. Kotthoff and D. Schütte (to be published)

number of diagrams (comp. Fig. 3). First of all, we have to deal with the crossed $\pi - \pi$ and $\pi - \rho$-terms. The main contributions come, however, from the so-called bloc diagrams in which the nucleon suffers a virtual excitation of the Δ-resonance state. These extremely long calculations indicate that the effect of the unphysical σ can be, to a large extent, replaced, leading thus to a complete boson theoretical interpretation of nuclear forces[7]. A remaining part which is due to the direct $\pi - \pi$ - interaction[8] has, however, still to be estimated. The results of these consideration suggest, at the same time, a natural interpretation of an important part of the nuclear interaction: The scattering process of two nucleons is strongly influenced by their polarization, i.e. virtual excitation of a resonance state. (Effects of this kind are well-known in the theory of chemical forces). Within the bound state this excitation might have - via the Pauli-principle - a characteristic effect on the single particle states of conventional shell structure.

5. Nuclear matter from the Bosonic Viewpoint

The decisive problem consists now in the introduction of these 2-boson exchange diagrams in the approximation scheme for nuclear matter[9]. In order to carry through this calculation, it is important to introduce explicitly the bosonic variables. This represents an extremely tedious and lengthy numerical calculation. As to be expected, the results for binding and density differ strongly from those obtained by the simplifying introduction of the σ-boson. The fact that the Pauli principle acts, so to speak, on the additional nucleon lines in the characteristic 2-pion diagrams (i.e. in all bloc diagrams with one nucleon line or the diagrams with crossed pion lines) has as a consequence that the binding energy is strongly reduced with respect to the simplified case. This repulsion is much stronger than the values obtained in first estimates, because there is also an essential contribution

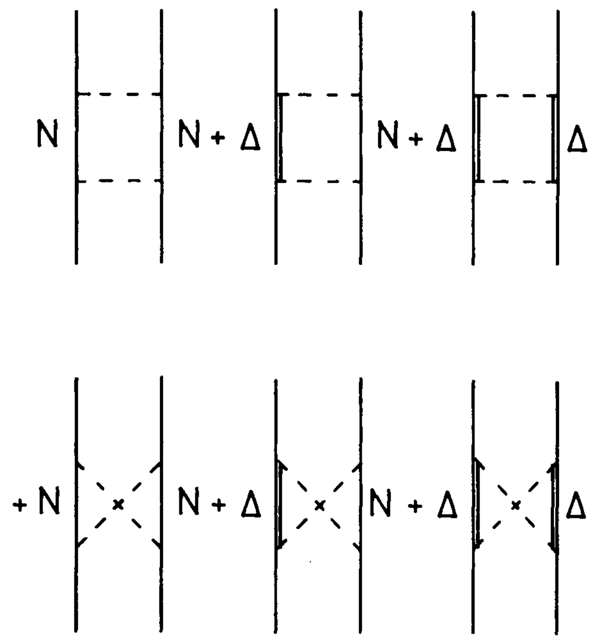

Fig. 3 Box diagrams with intermediate nucleons and Δ-isobars. The dotted lines represent the exchanged bosons especially π- and ρ-mesons

from the introduction of bosonic variables. At first sight there is thus a definite lack of binding energy, whereas the density appears to be quite reasonable. On the other hand, these calculations do not contain the higher terms of the hole-line expansion. A rough estimate through the introduction of the so-called "continuous choice"[10] for the energy of the particle states in the Brueckner scheme leads to a definite increase of the binding energy; nevertheless there is still an appreciable amount of binding lacking. A detailed analylis of this situation shows, however, that the boson propagator within nuclear matter has also to be changed with respect to the case of the exchange between free nucleons. In fact, the bosons within nuclear matter experience a characteristic change of their self energy through the typical bubble diagrams introduced also in the theory of boson condensation[11]. It may be foreseen that this effect contributes in an essential way to the binding energy. It is thus realized that the introduction of the 2-boson exchange into the theory of nuclear matter leads to appreciable modifications which might, eventually, bring the saturation point within the energy density diagram to the right position. On the other hand, the calculations have still to be completed with respect to the boson self-energy and the higher terms in the hole-line expansion.

6. A Solvable Model

In view of the formal complications of the boson theoretical method, it might be worth while to check this approximation scheme with the help of so-called solvable models. This corresponds to the introduction of a simplified field theoretical fermion-boson system which allows a rigorous solution. Applying then a given approximation scheme to this same model, the errors with respect to the exact values can be directly determined. Models of this kind generalizing the well-known Lee-model from field theory were introduced and discussed by D. Schütte and J. da Providencia[12]. In this framework it turned out that the terms changing the boson propagators are definitely needed in order to improve the convergence of the approximation scheme. The same model was also used in order to give an explicit representation of the boson condensation: It is, in fact, seen that a classical boson field is being generated as soon as the critical point has been passed. It is thus realized that the boson theory of nuclear matter leads to a rather extended research which is far from being solved completely. It should be stressed that the main part of nuclear binding is due to the virtual excitation of the nucleons and the characteristic change of the self energy of the bosons. In this respect it must be mentioned that the change of the bosonic self energy of the nucleons embedded into nuclear matter should also be taken into account. The corresponding terms appear, in fact, automatically in our enlarged boson theoretical scheme. (Calculations are under way).

7. Quark Theoretical Viewpoints

Eventually the phenomenological input to this theory should be discussed: The whole scheme is based on the properties of the various boson-nucleon vertices (including the Δ-resonance). This amounts to assume a relatively large number of coupling constants and form factors to be determined for the moment from experimental particle physics and to a large extent from a comparison with the empirical nucleon-nucleon scattering phases. In particular it should be stressed that the numerical values of the various form factors play a rather important role in the numerical results. In view of the enormous success of the quark-gluon structure of nucleons and bosons in the framework of modern particle physics, the question arises whether it might be possible to determine the various parameters of these vertices from this more fundamental viewpoint. Some first attempts of obtaining some coupling constants were already made[13]. The main problem which remains, however, is the fact that present day quark models (so-called bags) lead to form factors which appear too large with respect to the values which were introduced in the boson theory discussed here. We have the impression that the quark models of nucleons need an important refinement and readjusting to the problems of nuclear physics. As the radii of some conventional bags[14] are of the order of the relative distances of nucleons in nuclear matter, it was also suggested that the nucleons were to some extent dissolved into their constituents within nuclear matter forming a kind of a quark sea or quark bag. This assumption might correspond in a certain way to the fact that in conventional theory the nucleons are strongly excited and that the bosons change their properties in an essential way. Although it has been checked[15] that magic numbers could also be obtained from these large quark bags, it remains to be shown that a relatively strong clustering into 3-quark subsystems (surrounded by a sea of quark--antiquarks representing the boson cloud of the nucleons) should occur, at least on the surface of the nucleus, in order to understand the characteristic single particle levels of nuclear shell structure. In any case it seems to be clear that present day boson theory represents by no means the final step in our understanding of nuclear forces and nuclear matter but rather an important intermediate step.

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