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New developments in the study of few-nucleon systems

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The current status of the theoretical studies of the few-nucleon systems is reviewed. We show that in the study of the $A = 3, 4$ bound states the different methods have reached a great precision even when realistic Hamiltonians including two- and three-body interactions are considered. The description of scattering observables can be achieved with a similar accuracy, as shown by recent comparisons performed by several groups. The availability of bound and continuum states allows for interesting tests of new models of the nuclear interaction and for important studies of electro-weak reactions.

1. INTRODUCTION

The study of few–nucleon systems was already popular since the early days of nuclear physics. One of the main motivations is that, in many cases, it is possible to achieve numerically accurate solutions of the associated quantum mechanical problem, allowing for unambiguous comparisons between theory and experiments. Nowadays, these studies have the following main motivations: firstly, to understand and describe the interactions between nucleons; secondly, to predict the rates of reactions of astrophysical interest involving few nucleons; finally, light nuclei are also extensively employed as targets of electroweak probes. Such studies provide important sources of information on the nuclear and the nucleon structure.

At present, quantum cromodynamics (QCD) is considered to be the fundamental theory describing the strong interaction between quarks. However, we are not able to perform direct calculations of few nucleon problems starting from QCD, since at low energies it becomes extremely complicated to deal with (the study of two-nucleon systems using QCD is just moving the first steps [1]). Instead of this, the nucleons are considered to move non-relativistically and to interact via static potentials originated from the exchange of mesons. The interaction between nucleons is very complicated and a well founded theory of the nucleon–nucleon (NN) and the three–nucleon (3N) forces is still not achieved. The NN interaction is known at large distances, where the one–pion exchange potential (OPEP) is the dominant term. At shorter distances the situation is more involved. Usually one resorts to NN scattering experiments to obtain valid parameterizations in the inner regions [2–4]. However, going to $A = 3$ or larger systems, one finds the well established underprediction of the binding energy (BE), when the nuclear interaction is approximated by a sum of pair potentials. This is usually explained by the missing of 3N forces. The

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modeling of this part of the interaction is however still in an early stage [5,6].

More recently, other models of NN potentials, reproducing the NN observables with χ^2/datum still close to 1, have been developed. Between them, it is worth to mention the interactions derived from chiral Lagrangians [7,8], the non-local potential in r-space developed by Doleschall *et al.* [9,10], and the so-called "low-k" potentials [11].

All these potential models have to be tested primarily in the $A = 3, 4, \ldots$ systems. It is therefore very important to have powerful techniques for solving few-nucleon problems. This task is, however, complicated by the fact that the nuclear interaction is non central and strongly repulsive at short internucleon distances. Even the problem of calculating 3N bound and scattering observables for a given NN and 3N interaction model is rather complex. With the present availability of adequate computing systems, this problem can be considered almost completely solved [12] (there are some exceptions, such as the correct treatment of the Coulomb potential in $p-d$ scattering above the deuteron breakup threshold). The possibility of performing very accurate calculations of $N - d$ observables has stimulated an intense experimental study of this reaction, particularly dedicated to test and develop new models of 3N interaction.

For four nucleon (4N) systems the situation is not so satisfactory, although in the last few years some progress has been achieved. For example, only recently [13–16] different calculations of the ^{4}He BE agree at a level of accuracy of a few tenth of keV, as will be shown below. On the other hand, the theoretical solution of the 4N scattering problems still constitutes a challenging problem from the standpoint of nuclear few-body theory. Only very recently, calculations of the 4N observables using realistic models for NN and 3N forces become possible [16–18]. In most cases, the theoretical calculations are found to be strongly at variance with the experimental data. For example, the proton analyzing power A_y in $p - {}^3$He elastic scattering is underestimated by the theory at the peak by about 50% [17,18]. Other discrepancies between theory and experiment are discussed in Refs. [19–21].

The theoretical study of (low-energy) electroweak reactions has reached a rather high accuracy, too. Nowadays, there are very sophisticated models of the nuclear electromagnetic and weak transition operators, taking into account accurately the meson exchange current (MEC) contribution [22]. Moreover, the availability of very accurate bound and scattering state wave functions allows for a consistent treatment of initial and final state interaction effects (for large systems, this can be done using the Lorentz integral transform technique [23]). As a result, very accurate predictions for several processes as nuclear form factors, electro- and photo-disintegration of nuclei, radiative and weak capture reactions, etc., can be now performed.

In conclusion, after many years of studies, the theory of few-nucleon systems has reached a full maturity. The comparisons with the existing data allow for interesting insights of the origin of the strong force between the nucleons, on the dynamics of several kind of reactions (breakup, fusion, charge-exchange), etc. However, in most cases, the experimental data are old, with large uncertainties, and not taken in a systematic way. In the following, the need of suitable new experiments will be emphasized. We would like also to underline that, using the formalism of the chiral perturbation theory, the few-nucleon problems can have nowadays a close contact with fundamental quantities of QCD.

In this contribution, we would like to point out the major achievements of few-nucleon