THE THREE-NUCLEON BOUND STATE WITH MESONIC AND INTERNAL NUCLEONIC DEGREES OF FREEDOM*)

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The necessity for the inclusion of mesonic and internal nucleonic degrees of freedom in the description of the three-nucleon bound states $^3$H and $^3$He is discussed. Results obtained with these added degrees of freedom are given for the binding energy and e.m. form factors.

1. INTRODUCTION

Most few-body physicists may consider the three-nucleon system a tackled problem without challenge. It is theoretically described in terms of Faddeev equations which can be solved with quite satisfactory accuracy for realistic two-nucleon potentials. Most nuclear physicists who enjoy the wealth of nuclear phenomena are disappointed by the scarce physics of the three-nucleon system. Is the three-nucleon system still interesting?

The three-nucleon system is the theoretically best accessible nucleus, but its physics is not understood in detail. The consequences of this fact for the microscopic theory of nuclear phenomena in general have not been explored yet. In the classic format of nuclear structure the nucleus is viewed as a collection of non-composite nucleons. The nucleons interact nonrelativistically through instantaneous charge-independent two-body potentials. How well can this classic model, which is nonrelativistic and which freezes mesonic and internal nucleonic quark degrees of freedom, describe nuclear properties quantitatively? What are the dominant correction mechanisms for the classic picture of the nucleus? The three-nucleon system may provide partial answers to these fundamental questions of microscopic nuclear structure.

2. THE THREE-NUCLEON BOUND STATE — A TEST FOR MICROSCOPIC NUCLEAR STRUCTURE

I discuss four problems which arise in the classic description of the three-nucleon bound state. The problems are characteristic of similar problems in heavier nuclei.

(1) The $^3$H binding energy obtained from current two-nucleon potentials $[-7.38 \ (7.23) \text{ MeV from the Paris [1] (Reid soft-core (RSC) [2]) potential with all two-body partial waves included up to total angular momentum } I \leq 2, \text{ the experimental value being } -8.48 \text{ MeV}]$ is too small by more than 1 MeV. The $^3$He r.m.s. charge radius $[2.01 \ (2.02) \text{ fm for the Paris (RSC) potential, the experimental value being } 1.84 \pm 0.04 \text{ fm}]$ is too large by about 5%. Off-shell changes of the potentials can be made at small distances, where the potential is theoretically unknown. They may yield additional binding and squeeze $^3$He and $^3$H as required. But due to the change in r.m.s. radius the $^3$He charge form factor gets tilted at zero momentum transfer without essential change in its shape. Thus, any improvement of the $^3$H binding energy worsens the position of the first

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diffraction minimum in the $^3$He charge form factor compared to experiment and vice versa. This
correlation of problems is established with high confidence for the three-nucleon system [3],
it is reminiscent of the Coester-band [4] correlation between binding energy and nuclear size in
heavier nuclei.

(2) The theoretically calculated $^3$He charge form factor is in the secondary maximum and for
momentum transfers beyond lower than the experimental one by a factor of 2—3 as demonstrated
in fig. 1. Off-shell variations of the two-nucleon potential appear unable to cure this problem.
A point-proton density with a pronounced central depression [6], which no theoretical density
has shown yet, would be consistent with experimental data. The problem of the $^3$He charge form
factor is reliably established. It may be related to charge-density problems in heavier nuclei [7]
as $^{208}$Pb.

![Fig. 1. $^3$He charge form factor $F(q)$ as a function of momentum transfer $q$ calculated for the
Paris (solid curve) and RSC (dashed curve) potentials with all two-body partial waves up to total
angular momentum $I = 2$ included. The experimental data are from ref. [5].

Fig. 2. $^3$He magnetic form factor $F(q)$ as a function of momentum transfer $q$ calculated for the
Paris (solid curve) and RSC (dashed curve) potentials with all two-body partial waves up to total
angular momentum $I = 2$ included. The experimental data are from ref. [10].

(3) In the classic picture of the nucleus with charge-independent hadronic forces
charge-dependent effects are solely due to the e.m. one-photon exchange and to the neutron-
proton mass difference. In order to account for the true e.m. contribution to the $^3$He-$^3$H binding-
energy difference, the theoretical description of $^3$He and $^3$H has to account well for their sizes
and their charge form factors at small momentum transfers. In fact, most of the e.m. contribution
can reliably be related to the experimental charge form factors, and the experimental binding-
energy difference of 764 keV indeed turns out to be predominantly of e.m. nature. However,
a fraction of (81 ± 29) keV remains unexplained [8]. It indicates charge-symmetry breaking in
the hadronic nucleon-nucleon interaction. Unexplained binding-energy differences of the same
order of magnitude are also encountered in heavier mirror nuclei [9].

(4) The theoretical $^3$He magnetic form factor is in violent disagreement with the experimental
data as seen in fig. 2. Compared with the discrepancy to experiment, different two-nucleon poten-
tials yield only small changes in the form factor. It has been known for long that no nucleonic