Application of the chiral forces to elctroweak processes

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Sunday 3rd October, 2021

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CHAPTER 1

INTRODUCTION

In the second half of XX century physical society faced a problem of describing low-energetic nuclear reactions. Quantum chromodynamics (QCD) is hardly applicable here as it is nonperturbative at low energies what complicates a lot search for the solutions [1].

In the early 1990-ies Weinberg [2, 3] introduced an idea of using a most general Lagrangian satisfying assumed symmetry principles and in particular spontaneously broken chiral symmetry to describe nuclear interactions at low energies. This idea together with effective field theory (EFT) of QCD led to the development of Chiral effective field theory (χEFT) which nowadays has become one of the most advanced approach to describing nuclear reactions at low energies.

For the EFT it is very important to define a quantity, which powers will determine a perturbation order. In the χEFT there are two natural scales: so-called soft scale - the mass of Pion $Q \sim M_\pi$ and hard scale - $\Lambda_\chi \sim 1\ GeV$ (chiral symmetry breaking scale). The ratio between these two scales $(Q/\Lambda_\chi)^\nu$ is being used as an expansion parameter in χEFT with power ν.

Considering so-called irreducible (the diagrams that cannot be split by cutting nucleon lines), Weinberg [2, 3] came to the identity for the powers of such diagrams[1]:

$$\nu_W = 4 - A - 2C + 2L + \sum_i \Delta_i, \tag{1.1}$$

where

$$\Delta_i \equiv d_i + \frac{n_i}{2} - 2 \tag{1.2}$$

In 1.1, C is a number of pieces which are connected, L - the number of loops in the graph. In 1.2, n_i is a number of nucleon field operators, d_i - the number of insertions (or derivatives) of M_π.

CHAPTER 2

PLAN

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  - AV18
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Why we study few nucleon systems

The study of light nuclei for the decades has been serving as an easiest way to study NN systems and forces inside the atom. And convenient way to proceed may be an interaction of atom with other particles: elastic or inelastic scattering. It is possible to construct such an experiments and check if theory works. People take into account that interactions may be caused by different forces and therefore should be described in different ways. It can be either strong, weak or electromagnetic interaction. It depends on the type of particle being scattered and the target which reaction it is.

The strong nuclear force appear inside the nuclei and among others bound neutrons and protons together. The description of strong interactions is extremely difficult as it deals not only with nucleon, but with their constituents: quarks and gluons. Quantum Chromodynamics(QCD) is a modern theory describing strong interactions, but it has also its difficulties as it is not reliable at low energies ($Q^2 \lesssim 1GeV^2$) [4].

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Starting the study of 3- (and more) nucleon systems it was found that 2N force is not enough to describe the system and 3N force was introduced. The first applications of such a force showed that it brings sufficient contribution and cannot be ignored [5]. Whereas the first applications included only early "realistic" potential, the latter investigations only proved this statements [6, 7]. It was also used to construct four-nucleon (4N) bound state [8].

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BIBLIOGRAPHY

[1] R. Machleidt and D. R. Entem. Chiral effective field theory and nuclear forces. *Phys. Rept.*, 503:1–75, 2011.

[2] Steven Weinberg. Nuclear forces from chiral lagrangians. *Physics Letters B*, 251(2):288–292, 1990.

[3] Steven Weinberg. Effective chiral lagrangians for nucleon-pion interactions and nuclear forces. *Nuclear Physics B*, 363(1):3–18, 1991.

[4] B.L. Ioffe. Qcd (quantum chromodynamics) at low energies. *Progress in Particle and Nuclear Physics*, 56(1):232–277, 2006.

[5] W. GlÃ¶ckle. Effects of the two-pion exchange three-nucleon force in the triton and 3he. *Nuclear Physics A*, 381(3):343–364, 1982.

[6] V. G. J. Stoks, R. A. M. Klomp, C. P. F. Terheggen, and J. J. de Swart. Construction of high-quality nn potential models. *Phys. Rev. C*, 49:2950–2962, Jun 1994.

[7] R. B. Wiringa, V. G. J. Stoks, and R. Schiavilla. Accurate nucleon-nucleon potential with charge-independence breaking. *Phys. Rev. C*, 51:38–51, Jan 1995.

[8] A. Nogga, H. Kamada, and W. Glöckle. Modern nuclear force predictions for the α particle. *Phys. Rev. Lett.*, 85:944–947, Jul 2000.