Annals of Physics 367 (2016) 13–32

Contents lists available at ScienceDirect

Annals of Physics

journal homepage: www.elsevier.com/locate/aop

Range corrections in proton halo nuclei

Emil Ryberg [a], Christian Forssén [a,d,e], H.-W. Hammer [b,c], Lucas Platter [a,d,e,f,*]

[a] *Department of Fundamental Physics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*
[b] *Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[c] *ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany*
[d] *Department of Physics and Astronomy, University of Tennessee, Knoxville, TN 37996, USA*
[e] *Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[f] *Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA*

ARTICLE INFO

Article history:
Received 10 August 2015
Accepted 7 January 2016
Available online 14 January 2016

Keywords:
Halo nuclei
Charge radius
Radiative capture
Effective field theory

ABSTRACT

We analyze the effects of finite-range corrections in halo effective field theory for S-wave proton halo nuclei. We calculate the charge radius to next-to-leading order and the astrophysical S-factor for low-energy proton capture to fifth order in the low-energy expansion. As an application, we confront our results with experimental data for the S-factor for proton capture on Oxygen-16 into the excited $1/2^+$ state of Fluorine-17. Our low-energy theory is characterized by a systematic low-energy expansion, which can be used to quantify an energy-dependent model error to be utilized in data fitting. Finally, we show that the existence of proton halos is suppressed by the need for two fine tunings in the underlying theory.

1. Introduction

The quantitative description of both nuclear structure and reactions on the same footing is a major challenge of contemporary nuclear theory. With new experimental facilities such as FRIB and FAIR at the horizon, the task to find improved approaches for nuclear reactions has become very urgent.

---

[*] Corresponding author at: Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA.
E-mail address: lplatter@utk.edu (L. Platter).

http://dx.doi.org/10.1016/j.aop.2016.01.008

Ab initio approaches to calculate nuclear scattering observables are limited by the computational complexity of the nuclear many-body problem. Scattering models perform well but use a number of uncontrolled approximations that make the errors of such calculations difficult to quantify.

Faced with these problems, it is important to note that there are a number of systems in the chart of nuclei for which the effective number of degrees-of-freedom is significantly smaller than the number of nucleons. This phenomenon is known as clustering, with alpha clustering, e.g. in the Hoyle state of ^{12}C, being the most prominent example. Clustering becomes even more extreme for so-called halo nuclei which consist of a tightly-bound core nucleus and a few weakly-bound valence nucleons [1–4]. This reduction in the number of degrees of freedom is the signature of a separation of scales in the system. In the case of a one-nucleon halo nucleus, the scale separation is manifest in the small ratio of the one-nucleon separation energy and the binding and excitation energies of the core. For typical momenta on the order of the one-nucleon separation energy, it allows for a systematic low-energy expansion in the ratio of these two scales. This expansion can then be employed to calculate nuclear observables in a model-independent and systematically improvable manner. This approach is called halo effective field theory (Halo EFT) [5] when a field-theoretical approach is used for the construction of the interaction and the calculation of observables. Halo EFT employs the minimal number of degrees-of-freedom (core and valence nucleons) and parameterizes the interaction in terms of a few measurable parameters. In addition, so-called core polarization effects become important if the core has low-lying excited states. These can be taken into account by including excited states of the core as explicit degrees of freedom in the effective theory.

Neutron halo nuclei occur rather frequently in the chart of nuclei along the neutron dripline and the structure and reactions of a number of known and predicted one- and two-neutron halo systems in the Helium [5–8], Lithium [9–13], Beryllium [9,14,13], Carbon [9,15–17,13], and Calcium isotope chains [18] have been studied in Halo EFT.

Proton halo systems exist too, but are less common due to the delicate interplay between attraction from the strong interaction and the repulsion from the Coulomb interaction. The effects of the Coulomb interaction were first included into an EFT with contact interactions by Kong and Ravndal [19]. Proton halos were considered recently in Refs. [20–22]. The Coulomb interaction introduces a new scale into the problem that can be understood as a result of the presence of a Coulomb barrier. This new scale is referred to as the Coulomb momentum and it is given by the inverse of the Bohr radius of the system. The introduction of a Coulomb momentum can complicate the power counting since it interferes with the separation of scales. Higa et al. [23], e.g., treated the Coulomb momentum as a high-momentum scale in their study of α–α scattering. However, this treatment is not always appropriate. The correct scaling of the Coulomb momentum will always depend on the system to be considered.

In this paper, we will extend the calculation performed in Ref. [20] by including higher-order effects due to the finite range of the interaction between core and proton. We also consider higher-order electromagnetic interactions. Specifically, we will consider the charge radius of S-wave halo nuclei and radiative proton capture into a halo state. Our analysis of finite-range effects also addresses the question of why there are more neutron halos than proton halos in nature.

This manuscript is organized as follows. In Section 2, we introduce Halo EFT for S-wave systems and explain how the Coulomb interaction is included into calculations. In Sections 3 and 4, we apply Halo EFT to calculate the charge radius of proton halo nuclei and radiative proton capture, respectively. Results for the excited $1/2^+$ state of Fluorine-17 are presented in Section 5. In particular, we extract the threshold S-factor for radiative proton capture on ^{16}O into ^{17}F* and the corresponding asymptotic normalization coefficient. To this aim we employ an order-by-order fit to experimental radiative capture data at finite energies and we demonstrate how to quantify theoretical uncertainties within Halo EFT. We address the aforementioned issue of fine tuning in proton halo nuclei in Section 6. Finally, we summarize our findings in Section 7.

2. Theory

In Halo nuclei, the core and the valence nucleons are the effective degrees of freedom. The Halo EFT Lagrangian can therefore be constructed using only a core and a nucleon field. For proton halos