Physics Letters B 773 (2017) 332–335

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Lambda beta-decay in-medium

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ARTICLE INFO

Article history:
Received 7 August 2017
Received in revised form 17 August 2017
Accepted 17 August 2017
Available online 25 August 2017
Editor: J. Hisano

Keywords:
Nuclear structure
Hypernuclei
Beta-decay
In-medium change

ABSTRACT

Under the working hypothesis that the structure of a bound hadron is modified by its interactions with other hadrons, one may expect to see changes in carefully chosen observables. In the light of a recent proposal to measure the axial charge in the strangeness changing beta-decay of a bound Lambda hyperon, we examine the size of the change expected within the quark–meson coupling model. It is predicted to be significant.

1. Introduction

After more than a hundred years the search for a fundamental theory of nuclear structure is continuing. The traditional approach, based upon many-body theory using phenomenological nucleon–nucleon (NN) forces with parameters determined by fits to NN data and supplemented by a three-body force with parameters constrained by nuclear data, has proven very successful for light nuclei [1]. Chiral effective field theory, which builds upon the symmetries of QCD [2], is currently widely used and also successful for lighter nuclei [3]. For heavy nuclei the density functional approach, pioneered by Brink and Vautherin [4], is extremely widely used with hundreds of Skyrme forces in the literature [5]. Until recently these Skyrme forces have been purely phenomenological, with a sizeable number of parameters determined by fitting selected nuclear data. A common thread in all of these approaches is that the particles which feel these phenomenological forces have the same structure as free protons and neutrons.

Of course, at the present time no-one doubts that the correct underlying theory of nuclear structure is QCD and the fundamental degrees of freedom are quarks and gluons. In spite of the substantial advances being made in lattice QCD, there is as yet no way to calculate the properties of a nucleus like Uranium directly from QCD. Chiral effective field theory at least guarantees the symmetries of QCD but is currently limited to neutrons, protons and pions as the relevant degrees of freedom. We will be concerned with an alternate approach, which starts with confined quarks as the degrees of freedom. This model, known as the quark–meson coupling (QMC) model [6–8] has been developed over some decades, with successful applications to a variety of phenomena; from traditional nuclear structure, to hypernuclei [9], ω [10], η and η' [11–14] mesons bound in matter and the EMC effect [15,17], to cite just a few examples. Like the other approaches the QMC model reduces the many-quark problem to a problem involving many clusters of confined quarks. However, within the QMC model the structure of those clusters is self-consistently determined by the interactions of the confined quarks in them with the quarks in the neighbouring clusters.

In this approach the relativistic character of the mean fields is critical, with a scalar field producing very different effects on the internal dynamics of the clusters from those generated by a Lorentz vector mean field. Indeed, while the latter primarily redefines the energy and contributes to the spin–orbit force, the former modifies the Dirac wave functions of the valence quarks, enhancing their lower components and as a consequence opposing the applied scalar field; an effect parametrized in terms of a "scalar polarizability". In the QMC model the scalar polarizability is the prime mechanism leading to the saturation of nuclear matter. The connection between the modification of the internal structure of the clusters of quarks with nucleon quantum numbers and either three-body forces or density dependent effective forces was established a decade ago by constructing a density functional equivalent to the underlying quark theory [18]. However, it is only in the past

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http://dx.doi.org/10.1016/j.physletb.2017.08.052

year or so that the density dependent force derived from the QMC model [19], which itself has just a few parameters, was shown to produce a remarkably accurate description of the properties of atomic nuclei across the periodic table [20].

The recent developments of the QMC model have established that it is capable of providing a realistic description of nuclear properties. Yet underlying this more or less conventional density functional (the detailed form of the non-linearity of the derived density dependence is rather less conventional) is the prediction that the structure of the bound "nucleon" is changed by the interactions with the local medium. Within an extension of the approach based upon the NJL model [16] rather than the MIT bag, this has been shown to lead to a rather satisfactory description of the EMC effect, with predictions for an enhanced EMC effect in the spin structure function [17] and observable consequences for parity violating deep inelastic scattering [21]. It also leads to a dramatic correction to the Coulomb sum rule [22]. All of these predictions will be subject to experimental tests but given the dramatic revision of our view of nuclear structure implied by the model it is vital to test the predictions in as many different ways as possible.

Here we investigate a new signal of the predicted change in the structure of a bound nucleon which will hopefully be the subject of experimental investigation at J-PARC. In particular, we consider the change in the $\Delta S = 1$ axial charge which is involved in the beta-decay of a bound Λ-hyperon. Some decay modes of the Λ hyperon in nuclei have already been studied, of course. The mesonic and non-mesonic decay rates in ^{5}He, ^{12}C and various other nuclei have been studied at BNL, KEK and DAFNE and theoretical calculations for those decay rates have been carried out [23–26]. However, there has so far been neither a calculation nor a measurement of the beta-decay of Λ hypernuclei. This work is inspired in part by discussions with H. Tamura who is planning to propose such an experiment at J-PARC [27]. Of course, there is a great deal of interest already in the modification of the axial charge of the nucleon in-medium, especially as this quantity enters to the fourth power in the lifetimes associated with neutrinoless double beta-decay, which provides a promising window onto whether or not the neutrino is a Majorana particle [28]. By focussing on the beta-decay of a bound Λ-hyperon in nuclei with different mass numbers, one has the opportunity to separate the intrinsic change in the corresponding axial charge from other potential corrections, such as meson exchange currents.

2. Modification of the $\Delta S = 1$ axial charge

The calculation of the mean scalar and vector potentials within the QMC model has been explained in a number of places. Motivated by the Zweig rule, the model includes *only* the coupling of the σ, ω and ρ mesons to the u and d quarks, not the strange quark. This has proven remarkably successful in describing the properties of hypernuclei. We fix the coupling constants of these mesons to the light quarks so as to reproduce the saturation properties of symmetric nuclear matter, as well as the symmetry energy at saturation.

For the light quark in the final nucleon (following beta-decay) the quark has an effective mass modified by its coupling to the mean scalar field. This effective mass, m^*, is negative at all but the lowest densities but this creates no problems as the quark is confined in a cavity of radius R and the eigenenergy of the quark is positive. Denoting this eigenenergy as Ω_α/R, the corresponding Dirac wave function is

$$\phi_\alpha = \begin{pmatrix} f_\alpha(r) \\ i\vec{\sigma}.\hat{r}g_\alpha(r) \end{pmatrix} \frac{\chi}{\sqrt{4\pi}} \tag{1}$$

with

$$f_\alpha(r) = \mathcal{N}_\alpha \frac{1}{r} \sin\left[\sqrt{\Omega_\alpha^2 - (m^*R)^2}\,\frac{r}{R}\right]$$

$$g_\alpha(r) = \mathcal{N}_\alpha \frac{R}{(\Omega_\alpha + m^*R)r}\left(\frac{1}{r}\sin\left[\sqrt{\Omega_\alpha^2 - (m^*R)^2}\,\frac{r}{R}\right] - \frac{\sqrt{\Omega_\alpha^2 - (m^*R)^2}}{R}\cos\left[\sqrt{\Omega_\alpha^2 - (m^*R)^2}\,\frac{r}{R}\right]\right).$$

Here $\mathcal{N}$ is the normalization constant such that

$$\int_0^R r^2 dr \left(f_\alpha^2 + g_\alpha^2\right) = 1\,.$$

The eigenvalue is determined by the boundary condition $f(R) = g(R)$.

Because there is no coupling of the mean scalar field to the strange quark in the Λ hyperon, its wave function is exactly as given in the original MIT bag model. This wave function, which we write as

$$\psi_\alpha = \begin{pmatrix} \tilde{f}_\alpha(r) \\ i\vec{\sigma}.\hat{r}\tilde{g}_\alpha(r) \end{pmatrix} \frac{\chi}{\sqrt{4\pi}} \tag{2}$$

has exactly the same form as ϕ above but with the strange quark mass, m_s, replacing m^* and an appropriate normalization constant, $\tilde{\mathcal{N}}$.

Following a trivial calculation, the strangeness changing axial charge is then given by:

$$g_A(\Delta S = 1) = \int_0^R r^2 dr \left(\tilde{f}(r)f(r) - \frac{1}{3}\tilde{g}(r)g(r)\right). \tag{3}$$

To estimate the change in this axial charge arising from the change in the internal structure of the bound nucleon we recall that the quark effective mass in-medium depends on the σ field according to $m^* = m - g_{\sigma q}\sigma$. Here m is the light quark mass appearing in the MIT bag model Lagrangian density and, as it is only a few MeV, we set it to zero. The quark coupling is related to the (free) nucleon coupling, $g_{\sigma N}$, through

$$g_{\sigma N} = 3g_{\sigma q}\int_0^R d\vec{r}\bar{\phi}\phi = 3 \times 0.479\, g_{\sigma q}\,. \tag{4}$$

For the σ field we use a local density approximation which gives [19]

$$g_{\sigma N}\sigma = \frac{G_\sigma \rho}{(1 + dG_\sigma\rho)}\,, \tag{5}$$

with ρ the local density and $G_\sigma = g_{\sigma N}^2/m_\sigma^2$. In the above expression we have neglected small relativistic effects and retained the dominant many-body effect arising from the scalar polarisability, d [19]. Using the bag model boundary conditions, the radii of the N and Λ would differ by about 1%. In the case of the vector charge (see the following section), naively integrating over the common volume would lead to a violation of the Ademollo–Gatto theorem [29]. The origin of this problem is that the MIT bag model is not a simple Hamiltonian model but involves constraints (expressed through the two boundary conditions). A complete treatment of SU(3) symmetry violation in such a system would be extremely complicated. On the other hand, as shown explicitly for neutron beta-decay in Ref. [30], the procedure followed there,