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Hypernuclear currents in a relativistic mean-field theory

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Hypernuclei are studied in the mean-field approximation to an extended σ-ω (Walecka) model. The baryon current in systems with one Λ hyperon added to a closed-shell core of nucleons is calculated by treating the linear response of the core to the Λ in a local density approximation. The core is modified through the mixing of positive- and negative-energy nucleon wave functions and the result is a significant nucleonic contribution to the baryon current. This relativistic effect could be directly observable in measurements of the magnetic moments of hypernuclei with a deeply bound Λ.

There has recently been an increasing interest in relativistic effects arising in models of the nucleus based on the Dirac equation with strong scalar and vector potentials.[1-3] In particular, attention has been focused on areas for which relativistic predictions differ significantly from predictions in the traditional framework of nonrelativistic nucleons.[4] However, an unambiguous experimental signature of large potentials and other aspects of relativistic dynamics has been difficult to find.

A potentially fruitful source of different predictions from relativistic and nonrelativistic models involves nuclear currents. The reduced nucleon effective mass, M_N^*, in the nuclear medium (because of the large scalar field) results in a single-particle convection current enhanced by M_N/M_N^* compared to the nonrelativistic value. This enhanced current, when applied in a simple shell-model picture, leads directly to the long-standing problem of isoscalar magnetic moment predictions in the relativistic framework.[1]

This problem has been resolved recently[5] in the context of the σ-ω (Walecka) model with the realization that the enhancement of the single-particle current does not always imply an enhanced current for the nucleus as a whole. In particular, a valence nucleon added to a closed-shell nucleus modifies the core, and the core contribution to the total current essentially *counterbalances* the M_N/M_N^* enhancement of the valence particle current.[6] The core modifications result from the mixing of positive- and negative-energy nucleon wave functions in response to the added particle. The end result is a return to the simple nonrelativistic Schmidt moment predictions.

Although relativistic and nonrelativistic models yield similar results for the isoscalar magnetic moments, there is a fundamental difference between these approaches. In the relativistic picture, the Schmidt values are obtained as a result of two *canceling* effects, while they arise *directly* in the nonrelativistic shell model. Thus, it is desirable to find cases for which these underlying theories have different predictions. We propose that hypernuclei may provide such a case.

In this note, we consider the addition of a Λ hyperon to a closed-shell nucleus. This involves the application of the σ-ω model to hypernuclear physics, which is an area of great interest in nuclear science.[7] We work with an extended Walecka model in the mean-field approximation, in which Λ hyperons couple to the same scalar and vector fields as the nucleons, but with different coupling strengths. A number of authors[8] have applied this model to hypernuclear studies and have obtained interesting results. In this work we find that, unlike the nucleons-only system, the relativistic core response does not cancel the enhancement of the single-particle current due to the Λ. This raises the possibility of an experimental signature of relativistic dynamics (e.g., the large potentials).

We examine the consequences for magnetic moments of Λ hypernuclei, which may provide an experimentally feasible[9,10] signature. Since the Λ is a neutral particle, it contributes directly to the magnetic moment of the hypernucleus only through its anomalous moment. In an extreme single-particle shell model, this is the only contribution (for a Λ added to a closed-shell nucleus), and gives rise to the "Schmidt moment" [$-(j/j+1)\mu_\Lambda$ for the Λ in a state with $j=l-\frac{1}{2}$ and μ_Λ for $j=l+\frac{1}{2}$]. But while the enhanced Λ single-particle convection current is not easily detected, the modification of the nuclear core *will* produce deviations from the Schmidt values which depend on the strengths of the meson potentials. We have calculated the expected deviations for a variety of hypernuclei (see Table I).

In addition to providing possible tests of relativistic models of nuclei, the present work also has an important implication for theoretical predictions of hadronic properties in nuclear matter. It has been suggested[9,10] that a measurement of the magnetic moment of a nucleus such as ${}^{209}_{\Lambda}$Pb, with the Λ in the $1s$ state [produced through $(e,e'K^+)$], will provide a direct test of changes in the properties of hadrons in the nuclear environment. Such theories are frequently invoked to explain quasielastic and deep inelastic lepton scattering results. We note that the proposed experiment will be ambiguous without a careful consideration of other effects that might produce deviations from the Schmidt values. The present study deals with the *relativistic corrections* in a model in which the nucleus is composed of hadrons (nucleons, a Λ hyperon, and mesons).

We now present an outline of the relativistic hypernuclear formalism. This is an extension of the nuclear case, and we closely follow the formalism of Ref. 6. (Additional details on the notation and methods can be found in Refs. 2 and 6.) We start with the mean-field theory (MFT) Lagrangian density for nucleons and Λ in the presence of a scalar field ϕ_0 and a vector field $V^\mu=(V_0,\mathbf{V})$ (note that maintaining the three-vector component of V^μ is crucial in our discussion):

$$\mathscr{L}_{\rm MFT}=\bar\psi_{\rm N}[\gamma_\mu(i\partial^\mu-g_v^{\rm N}V^\mu)-(M_{\rm N}-g_s^{\rm N}\phi_0)]\psi_{\rm N} +\bar\psi_\Lambda[\gamma_\mu(i\partial^\mu-g_v^\Lambda V^\mu)-(M_\Lambda-g_s^\Lambda\phi_0)]\psi_\Lambda + \text{purely mesonic terms}, \quad (1)$$

where the meson-baryon coupling constants for nucleons and hyperons may differ. Since no strange mesons are included in this model, the nucleon current, $\bar\psi_{\rm N}\gamma^\mu\psi_{\rm N}$, and the Λ current, $\bar\psi_\Lambda\gamma^\mu\psi_\Lambda$, are *separately* conserved. The MFT equations for the baryon and meson fields in nuclear matter are obtained following the usual procedures,[2] and spinor solutions to the baryon equations are readily constructed for nuclear matter. The spinors are *independent* of V_0 but depend on ϕ_0 and $\mathbf{V}$.[2,6]

We consider nuclear matter in a large volume Ω with one Λ added as a model of the system of interest: a Λ added to a closed-shell nucleus. We start with a discussion based on perturbation theory, in order to clarify the physical origin of the relativistic core response and to motivate a more formal treatment. As our unperturbed system we take a filled Fermi sphere of nucleons for which a solution exists in the Hartree approximation[2] (zeroth order) and to which the Λ hyperon contributes a perturbing Hamiltonian δh. The unperturbed core of nucleons does not contribute to the baryon current. The extra hyperon changes the meson fields by $\delta\phi_0$ and δV^μ, which are proportional to $1/A$ or $1/\Omega$, where Ω is the volume of the system. To first-order in perturbation theory the positive-energy spinor matrix elements of δh are diagonal and do not modify the zeroth-order (closed shell) Hartree single-particle wave functions. However, we must consider the contributions of the negative-energy spinor solutions as well. The matrix elements of δh between the positive- and negative-energy spinors are nonzero, thereby changing the single-particle wave functions, which generate a contribution to the current from the core. *This type of core response (modification of the single-particle wave functions) is not possible nonrelativistically in nuclear matter.*

We note that these features are *automatically incorporated* in a self-consistent Hartree solution of the entire system (core $+\Lambda$). However, since this problem is difficult to solve in a finite system (spherical symmetry is lost), we build instead upon the closed-core self-consistent solution and correct it to leading order in the spirit of the fully self-consistent (core + valence) calculation.

We focus our discussion on the baryon current $\mathbf{j}_B=\mathbf{j}_{\rm N}+\mathbf{j}_\Lambda$, which is related to $\mathbf{V}$ in the MFT through

$$\mathbf{V}=\frac{g_v^{\rm N}}{m_v^2}\mathbf{j}_{\rm N}+\frac{g_v^\Lambda}{m_v^2}\mathbf{j}_\Lambda ,$$

where m_v is the vector (ω) meson mass. To zeroth order, the core does not contribute to the baryon current, and we find an *enhanced current* contributed by the valence hyperon:

$$\Omega\mathbf{j}_B^{(0)}=\left[\sum_{\mathbf{k},\lambda}^{k_F}\mathscr{U}_{\rm N}^\dagger(\mathbf{k},\lambda)\boldsymbol{\alpha}\mathscr{U}_{\rm N}(\mathbf{k},\lambda)\right]+\mathscr{U}_\Lambda^\dagger(\mathbf{t},\lambda)\boldsymbol{\alpha}\mathscr{U}_\Lambda(\mathbf{t},\lambda) =0+\frac{\mathbf{t}}{E_t^{\Lambda *}} , \quad (2)$$

where $\mathscr{U}_B$ are the positive-energy Dirac spinors, k_F is the Fermi momentum, $\mathbf{t}$ is the momentum of the valence Λ, and $E_t^{\Lambda *}=(\mathbf{t}^2+M_\Lambda^{*2})^{1/2}$. As noted above, this enhancement in the nucleons-only system gives rise to the well-known problem of the magnetic moments.[1] However, self-consistency requires that the effects of the valence particle on the core be taken into account. The first-order correction to the baryon current results from the mixing by $\delta\mathbf{V}$ of negative- and positive-energy single-particle wave functions. Evaluating this contribution (which is as large as the valence particle contribution, because all core nucleons are involved) we find

$$\Omega\mathbf{j}_B^{(1)}=\mathscr{U}_\Lambda^\dagger(\mathbf{t},\lambda)\boldsymbol{\alpha}\mathscr{U}_\Lambda(\mathbf{t},\lambda)\left[1-\frac{g_v^{\rm N}g_v^\Lambda}{m_v^2}\frac{\rho_{\rm N}}{E_{k_F}^{\rm N *}}\right] , \quad (3)$$

where $\rho_{\rm N}=2k_F^3/3\pi^2$ and $E_{k_F}^{\rm N *}=(k_F^2+M_{\rm N}^{*2})^{1/2}$.

At this stage it is clear that the core corrections will not entirely cancel the enhancement of $\mathbf{j}_B^{(0)}$, since the mass of the Λ and its couplings to the meson fields are different from those of the nucleon. This result is to be contrasted with the nuclear situation, where the core response essentially cancels that enhancement.[5,11] Thus, the effects of the strong fields in relativistic models may actually be observed by introducing a strange particle into the system. Since the Λ is isoscalar, the effects are relatively clean and free of ambiguities (unlike the isovector case, which is plagued by numerous theoretical uncertainties).

Since the effects of the modified core can be large, it is necessary to go to higher orders in perturbation theory. This is most efficiently done using Green's function methods. In this approach, the Hartree approximation corresponds to the self-consistent summation of tadpole contributions to the baryon self-energy. Calculating the Hartree propagator exactly for the core $+\Lambda$ system is difficult, so we start with the Hartree solution for the core alone and add an extra particle (the Λ) to this system. If we assume an inert core but let the valence Λ interact with the core meson fields, we recover the enhanced current [Eq. (2)]. The fields produced by the valence particle modify the propagator of the core. The total core linear response is determined by the polarization insertion (the RPA ring at zero energy) computed with the nucleon Hartree propagator (Fig. 1). For nuclear matter, where the perturbations are static and uniform, we need the response functions only at zero four-momentum transfer. *This linear response involves only the mixing of positive- and negative-energy wave functions and is a static response that cannot occur in a nonrelativistic theory of nuclear matter.*

We can identify the perturbation theory result with the

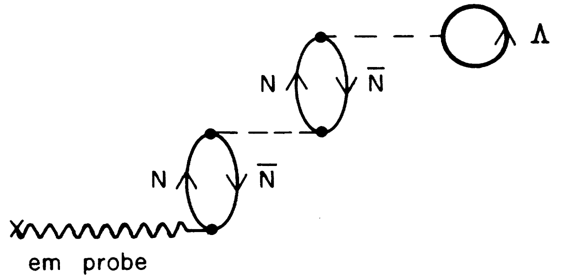

FIG. 1. Typical contribution to the relativistic core response correction. The rings indicate the mixing of positive-energy core states (N) with negative-energy solutions ($\bar{N}$). The heavy closed line represents the Λ wave function calculated in the meson fields of the core and the dashed line is the ω-meson propagator. The full correction is obtained by summing the rings to all orders.

lowest-order ring contribution (Π_0) to the linear response function (Π) at zero momentum transfer and, indeed, to first order in the ring summation we obtain Eq. (3). Summing the rings to all orders, we obtain the RPA response (Fig. 1):

$$\Pi=\frac{\Pi_0}{1-\left[\frac{g_v^{\mathrm{N}}}{m_v}\right]^2\Pi_0}\,, \tag{4}$$

where

$$\Pi_0=-\frac{\rho_{\mathrm{N}}}{E_{k_F}^{\mathrm{N}*}}\,.$$

To obtain the total baryon current we replace Π_0 by Π in the expression for the baryon current [Eq. (3)], which yields

$$\begin{aligned}\Omega \mathbf{j}_B &= \mathscr{U}_\Lambda^\dagger(t,\lambda)\boldsymbol{\alpha}\mathscr{U}_\Lambda(t,\lambda)\left[1+\frac{g_v^{\mathrm{N}}}{m_v^2}\frac{(g_v^{\mathrm{N}}-g_v^{\Lambda})\rho_{\mathrm{N}}}{E_{k_F}^{\mathrm{N}*}}\right]\\ &\quad\times\left[1+\left[\frac{g_v^{\mathrm{N}}}{m_v}\right]^2\frac{\rho_{\mathrm{N}}}{E_{k_F}^{\mathrm{N}*}}\right]^{-1}\\ &= \mathscr{U}_\Lambda^\dagger(t,\lambda)\boldsymbol{\alpha}\mathscr{U}_\Lambda(t,\lambda)\left[1+\frac{g_v^{\Lambda}}{g_v^{\mathrm{N}}}\frac{\left[\frac{g_v^{\mathrm{N}}}{m_v}\right]^2\Pi_0}{1-\left[\frac{g_v^{\mathrm{N}}}{m_v}\right]^2\Pi_0}\right]. \end{aligned}\tag{5}$$

The total core correction for this hypernuclear case is a factor of $g_v^{\Lambda}/g_v^{\mathrm{N}}$ times the correction found for nucleons only. Note that the enhanced valence particle current is not cancelled by the core contribution.

It is important to note that not all nuclear observables are affected by considerations of the core response. For example, upon calculating the time-like component of the current (the baryon density) we find $\Omega\rho_B=A+1$ which already includes the extra baryon. This extra density results solely from the single-particle (Λ) current, and there is no correction from the polarized core (specifically, the zero-zero component of the vector-meson polarization insertion vanishes). Similarly, the calculated single-particle energies and the spin-orbit force[8] are not sensitive to this effect. In practice, extensive observables derived from the momentum or baryon current are likely to have important corrections, while in calculating intensive observable one can safely use the inert-core Hartree solutions.

The effects of core modifications can best be detected electromagnetically. We adopt the effective electromagnetic current of Refs. 2 and 6 for use with our model. The Λ has no charge, so the Schmidt value for the magnetic moment results from only the anomalous magnetic moment of the Λ ($\mu_\Lambda=-0.613$ nm). The valence-particle current is not observed and the anomalous magnetic moment is not modified in the present model. But we must include the relativistic core response current, which modifies the electromagnetic current and the magnetic moment. Following Ref. 6, we include these effects in a local density approximation (LDA) to the isoscalar convection current, using the result found for nuclear matter [Eq. (5)]. The total electromagnetic current is then

$$\begin{aligned}\langle \mathbf{J}(\mathbf{x})\rangle &= \frac{\mu_\Lambda}{2M_{\mathrm{N}}}\nabla\times\{U_\Lambda^\dagger(\mathbf{x})\beta\boldsymbol{\Sigma}U_\Lambda(\mathbf{x})\}\\ &\quad-\tfrac{1}{2}U_\Lambda^\dagger(\mathbf{x})\boldsymbol{\alpha}U_\Lambda(\mathbf{x})\frac{g_v^{\Lambda}}{g_v^{\mathrm{N}}}\left[1+\left[\frac{m_v}{g_v^{\mathrm{N}}}\right]^2\frac{E_{k_F}^{*\mathrm{N}}}{\rho_{\mathrm{N}}(\mathbf{x})}\right]^{-1}, \end{aligned}\tag{6}$$

where $U_\Lambda(\mathbf{x})$ is the Hartree single-particle solution for the Λ in the meson fields of the closed-shell nucleus.[2] Using this current, we calculate the magnetic moments of the hypernuclear system. Since we work in a relativistic (four-component) formalism, there is no model-independent separation of "orbital" and "spin" contributions to the magnetic moment. Note that any significant deviations from the Schmidt value $[-(j/j+1)\mu_\Lambda$ for the Λ in a state with $j=l-\frac{1}{2}$ and μ_Λ for $j=l+\frac{1}{2}]$ indicate a relativistic effect proportional to the strength of the ω potential.

The calculations presented here use the finite Hartree parameters from Ref. 2 for the nucleon-meson couplings. These are relevant for a σ-ω model extended to include a neutral rho meson and the Coulomb potential (which couple only to nucleons). The extended model provides good fits to the bulk properties of closed-shell nuclei.[2] This extension does not change the previous discussion. We choose the Λ-meson couplings so that $g_s^{\Lambda}/g_s^{\mathrm{N}}=g_v^{\Lambda}/g_v^{\mathrm{N}}=0.4$. These values are consistent with good fits to available experimental hypernuclear spectroscopic data, orbitals, and Λ-particle—nucleon-hole energies.[12] Note that the central Λ-potential is weaker than the nucleon one and the Λ single-particle states are less bound than the corresponding nucleon states. The spin-orbit splitting is very small in this model, in accord with experiment: in ${}^{17}_{\Lambda}\mathrm{O}$ we find that the binding energies of the Λ hyperon states are approximately -13.0 MeV for the $1s_{1/2}$ state and -2.4 and -1.4 for the $1p_{3/2}$ and $1p_{1/2}$ states.

The predicted magnetic moments for hypernuclei rang-

TABLE I. Magnetic moments of Λ hypernuclei in units of nuclear magnetons (μ_N).

		Magnetic moment (μ_N)					
Λ s.p. state	Schmidt	${}^{13}_{\Lambda}$C	${}^{17}_{\Lambda}$O	${}^{41}_{\Lambda}$Ca	${}^{91}_{\Lambda}$Zr	${}^{209}_{\Lambda}$Pb	$A=\infty$
$1s_{1/2}$	−0.613	−0.650	−0.648	−0.665	−0.676	−0.681	−0.689
$1p_{3/2}$	−0.613	−0.633	−0.644	−0.690	−0.725	−0.742	−0.765
$1p_{1/2}$	0.204	0.190	0.179	0.163	0.164	0.169	0.179
$1d_{5/2}$	−0.613	−0.616	−0.616	−0.681	−0.751	−0.792	−0.838

ing from ${}^{13}_{\Lambda}$C to ${}^{209}_{\Lambda}$Pb are given in Table I along with the nonrelativistic Schmidt values. If the core response is not included, the calculated moments for all nuclei are within $\sim 1\%$ of the Schmidt values [with the small variations resulting from the lower components of $U(\mathbf{x})$]. The last column, labeled $A=\infty$, lists the values obtained from a calculation where the core contribution is a constant, evaluated at nuclear matter density, as would be obtained for a deeply-bound Λ in a very large nucleus.

Several observations can be made based on Table I. As expected, heavy nuclei are the best place to look for the core response effects. In particular, nearly the maximum possible effect on the $1s_{1/2}$ state is found to occur in ${}^{209}_{\Lambda}$Pb. This $1s_{1/2}$ state is also a plausible candidate for an experimental measurement[9,10] at CEBAF and the proposed ALS SUPRA in France.[13] This measurement will put important constraints on the relativistic treatment of nuclei as well as the application of QCD-motivated models to nuclei

The other Λ-single-particle states listed in Table I are principally of theoretical value, since we do not anticipate actual measurements for these states. It is, however, interesting to note that the potential maximum effect for $j=1+\frac{1}{2}$ states is larger for higher j single-particle states (the effect goes as $2j+1$). This maximum would not be approached in actual nuclei, though, because of the reduced nucleon density at the nuclear surface and beyond. If the Λ is in a $1p_{1/2}$ state $(j=1-\frac{1}{2})$, the Λ single-particle convection current $U_{\Lambda}^{\dagger}(\mathbf{x})\boldsymbol{\alpha}U_{\Lambda}(\mathbf{x})$ which appears in Eq. (6) has a radial node. The net correction in this case depends on the location of the node relative to the nuclear surface because the core response is proportional to the nuclear density. We find that the correction for the $1p_{1/2}$ state is a maximum around calcium.

To avoid possible confusion, we note that our calculation has been performed for a closed-shell nuclear core plus an extra Λ hyperon. It is possible to apply the same ideas to a calculation involving the creation of a Λ on a closed-shell nucleus. For example, we could consider a closed-shell core with a nucleon hole plus a Λ hyperon, such as ${}^{16}_{\Lambda}$O. This calculation, however, is more complicated than the present work and is subject to greater uncertainties because of additional nuclear structure effects. The calculations of relativistic core response effects calculated here are relevant for measurements performed on closed-shell plus Λ hypernuclei.

In summary, we have studied three-vector currents in hypernuclear systems with one Λ added to a closed-shell core of nucleons in the mean-field approximation to an extended σ-ω model. We find that the relativistic core response does not cancel the enhanced single-particle current due to the valence hyperon, unlike the case of nucleons only. Furthermore, since the Λ is an isoscalar, it is possible to directly probe the modified core current electromagnetically;[14] for example, by measuring the deviations of the magnetic moments of hypernuclei from the Schmidt values (see Table I). Since deviations are also predicted in other models through different effects (e.g., increases in baryon size in nuclear matter), measurements of magnetic moments of hypernuclei[10] can provide important tests of different pictures of nucleons and nuclei. Experiments of this sort should be suitable for the next generation of nuclear physics facilities.

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[11]This cancellation is not accidental and has its roots in the basic feature of the model: two large potentials of opposite sign, almost balancing each other to yield the small binding energies of nucleons in nuclei.

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[14]Since the Λ hyperon is subject to the weak interaction, one might wonder if these effects would be seen through the weak currents, for instance in nonmesonic decays of hypernuclei. Because of the isovector nature of weak processes, this question cannot be adequately studied in the present simple model which includes only isoscalar mesons. (As noted above, isovector currents are difficult to calculate reliably because of large corrections from other nuclear effects.)