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Mapping Neutron Drip Lines in Meson Field Theories

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Abstract

The binding energy and axial deformation of medium-light nuclei and Λ hypernuclei are investigated within different relativistic meson field theories. In particular, the effect of including Λ hyperons in neutron-rich nuclei near the neutron drip line is investigated. Using the NL3* parameter set ^{30}Si, ^{32}S, and ^{34}S change from a deformed state to spherical shape by adding a single Λ to the respective nuclei. Similarly, ^{28}Si becomes spherical when adding two Λ's to the nucleus. In other parameter sets the nuclear deformation β_2 is reduced by adding a Λ . In addition, the location of the neutron drip lines for both ordinary and hypernuclei in the region of neon to argon are predicted.

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1. INTRODUCTION

In recent years there has been increased interest in the study of radioactive nuclei far beyond the valley of stability, extending to exotic high-isospin, neutron-rich isotopes of nuclei and eventually hypernuclei. Especially with the upcoming future facilities FAIR at GSI and FRIB at MSU a large amount of new data in this regime is expected in the coming years. As more and more neutrons are added to a given nucleus, the neutron binding energy will eventually become negative, leading to the emission of neutrons. This then defines the boundary for particle-stable nuclei, usually termed as the neutron drip-line (with its counterpart on the proton rich side, the proton drip-line) [1]. In addition, a strong interest in the study of neutron-rich hypernuclei has developed, experiments along this line are planned by the HyPHI collaboration [2].

Currently, about 3,000 isotopes have been experimentally studied [3]. However, the location of the neutron drip line, in the case of normal nuclei and much more so for hypernuclei, is an open question. The investigation of the proton drip line is somewhat easier compared to the neutron case, because electric repulsion severely restricts the number of protons for a given neutron number [4]. The neutron drip line, on the other hand, is far away from the β stability line, rendering its experimental study very challenging. Furthermore, as the neutron to proton ratio along the valley of stability increases for heavier nuclei, the number of neutrons that can theoretically be added to a nucleus also increases substantially towards heavier elements. Beyond oxygen, the drip line has been tentatively assigned for elements up to sodium (Z=11) with a possible maximum of 26 neutrons. Baumann et al. reported the discovery of two more neutron-rich isotopes: a magnesium isotope ^{40}Mg (N = 28) and an aluminium isotope ^{42}Al (N = 29).

In the following we study the properties of medium-heavy isotopes with large neutron number, where we compare a rather recently developed parameter set within a relativistic mean-field approach (NL3*) [5]. Another important aspect in the study of exotic nuclei is the extension to hypernuclei into this neutron-rich regime. In addition, many questions in heavy-ion physics and astrophysics are related to the effect of strangeness in matter. By adding a Λ hyperon no Pauli blocking occurs, therefore serving as an excellent probe of the inner structure of the nucleus. As the wave function of the Λ in its lowest state is spherical a deformed nucleus can in principle change its shape towards smaller deformation through the addition of a Λ. To get a better qualitative understanding of hypernuclear structure in this regard, this work investigates the connection between the axial deformation of Λ hypernuclei.

2. MODEL DESCRIPTION

An often-used approach to study the properties of finite nuclei and nuclear matter is given by self-consistent relativistic mean field theory based on effective mesonic interactions, which we will employ in the present work. For this purpose we consider an optimized parameterization of a non-linear Walecka model, NL3* [5], and a more fundamental approach within a chirally symmetric description, where the baryonic masses are generated through spontaneous symmetry breaking and the coupling of the baryons to non-vanishing scalar meson fields in the vacuum (parameter set χ_m [6]). Both approaches have been shown to yield good quantitative results for a large range of nuclei [5, 6]. In both formulations nucleons interact in a relativistic covariant manner through the exchange of isoscalar scalar self-coupling σ meson, the isoscalar vector ω meson, the isovector-vector ρ meson, and the photon. The role of relativity in the short-range region of the nuclear force and its effect in producing saturation at the correct density and binding energy in nuclear matter has been discussed in [7]. One further conceptual advantage of relativistic approaches is that they generate a large nuclear spin-orbit interaction in a very natural way arising from the meson-nucleon interactions.

2.2.1 Walecka-type model

In one part of our calculation, we use a Walecka-type model in which protons and neutrons are described as point-like Dirac particles interacting in a relativistic covariant manner through the exchange of various mesons including the isoscalar-scalar σ meson, the isoscalar-vector ω_μ meson, the isovector-vector ρ_μ meson and in addition the photon A_μ [8, 9]. In our numerical calculations we solve the corresponding equations of motion for the baryons and the mesonic mean fields. This includes the Dirac equation for the baryons with the couplings to the scalar and vector fields:

$$\left\{\gamma^\mu\left(i\,\partial_\mu + g_\omega\omega_\mu + g_\rho\tau\rho_\mu + e\frac{1+\tau_3}{2}A_\mu\right) + (M + g_\sigma\sigma)\right\}\psi_i = 0 \qquad (1)$$

where in the static case only the 0^{th} component of the vector fields and only the neutral rho meson contribute ($\omega^0 = \omega$, $\rho^0 = \rho$). For the meson fields and the photon we solve the Klein Gordon equations, which read

$$\begin{aligned}
(-\Delta + m_\sigma^2)\sigma(\mathbf{r}) &= -g_\sigma\rho_s(\mathbf{r}) - b_2\sigma^2(\mathbf{r}) - b_3\sigma^3(\mathbf{r}),\\
(-\Delta + m_\omega^2)\omega(\mathbf{r}) &= g_\omega\rho_b(\mathbf{r}) + b_4\sigma\omega^2(\mathbf{r})\omega(\mathbf{r}),\\
(-\Delta + m_\rho^2)\rho(\mathbf{r}) &= g_\rho\rho_i(\mathbf{r}),\\
-\Delta A^0 &= e\rho_q
\end{aligned} \qquad (2)$$

with the corresponding charge, scalar, vector and isovector-vector densities ρ_q, ρ_s, ρ_b and ρ_i, respectively. In order to investigate open-shell nuclei, a δ-force BCS pairing is applied [10] . For the investigation of hypernuclei, we added Λ's as baryonic degrees of freedom in Eq. (1) . The corresponding meson-Λ coupling strengths were fixed by assuming the SU(6) relation for the Λ and nucleon vector couplings, i.e. $g_{\Lambda\omega} = 2/3\ g_{N\omega}$ and adjusting the couplings to the scalar field in order to obtain a realistic nuclear matter binding energy of the Λ, which we checked by comparing the results for the nucleus ${}^{209}_{\Lambda}Pb$ with data. In our numerical code the set of coupled non-linear equations for the nucleons (plus hyperon for hypernuclei) are solved on a two-dimensional spatial grid in order to accommodate for axially symmetric nuclear deformation, using a self-consistent iteration method. In order to study the dependence of the binding energy on the axial deformation of nuclei and hypernuclei explicitly, we perform a calculation with a constraint on the quadrupole deformation of the nucleus. We vary the constraint and determine the energy of the various isotopes as function of deformation [6,10].

2.2.2Chiral model

The effective chiral model used here is a hadronic model based on a chiral SU(3) formulation, using a nonlinear realization of chiral symmmetry (a detailed discussion can be found in [6]). Analogously to Walecka models, the baryons and mesons represent the basic degrees of freedom, in this case including the complete sets of the lowest-energy SU(3) multiplets for the various quantum numbers. This comprises the baryon octet B, which contains nucleons and the Λ, Σ and Ξ hyperons, and the respective multiplets of scalar, pseudoscalar, vector and axial vector mesons. The mesons that mediate the interactions between the baryons relevant for this work, are the vector isoscalar ω and ϕ, the vector isovector ρ and the scalar isoscalar σ ($f_0(600)$) and ς ($f_0(980)$). The baryon multiplet couples to the various mesonic multiplets according to the general flavor-SU(3)-invariant scheme. In addition, the mesons have self-interaction terms that in the case of the scalar fields generate the spontaneous symmetry breaking due to non-vanishing expectation values in the vacuum [6]. Adopting mean field approximation for the calculation of static nuclei and hypernuclei the following fields have to be take into account: The proton, neutron, and Λ, the scalar meson fields $\sigma \sim (\bar{u}u + \bar{d}d)$ and , $\zeta \sim (\bar{s}s)$ the isovector

$\delta \sim (\bar{u}u - \bar{d}d)$, the time components of the isoscalar and isovector mesons ω and ρ, and the Coulomb field A_0. By restricting ourselves to those degrees of freedom the general SU(3) Lagrangian reduces to the following structure. The interaction term of the baryons and mesons (and the photon) reads:

$$\mathcal{L}_{int} = -\sum_i \bar{B}_i\left[g_{i\omega}\omega\gamma_0 + g_{i\rho}\tau_3\rho\gamma_0 + \tfrac{1}{2}e(1+\tau_3)A_0\gamma_0 + m_i^*\right] B_i \qquad (4)$$

Due to their interaction with the scalar fields, the baryons obtain a dynamically generated mass. Similarly to the Walecka models, this mass generally changes in the nuclear medium. The effective baryon masses are given by

$$m_i^* = g_{i\sigma}\sigma + g_{i\delta}\delta + g_{i\zeta}\zeta \qquad (5)$$

The values for the various couplings contained in Eqs (4) and (5) can be found in [6].

3. MAPPING NEUTRON DRIP LINES

The proton and neutron drip lines define the limits of existence for particle-stable nuclei. Baumann and et. al. reported a significant advance in defining the neutron dripline through the measurement of two neutron-rich isotopes – ^{40}Mg and ^{42}Al - that are predicted to be dripline nuclei in some approaches [11]. The discovery of ^{40}Mg and the observed nucleus ^{44}Si [12] are in agreement with our prediction of the neutron drip line in the chiral model with the parameter set χ_m. Here, we study the results for the nuclear region from neon to argon for the chiral model in comparison with the newly tuned non-linear Walecka (RMF) model NL3*. Using our results for the nuclear binding energies we determine the two-neutron separation energies for the chain of Ne-Ar isotopes in RMF theory as shown in Fig. 1. Two-neutron separation energies for nuclei and hypernuclei have the same general characteristics. The two-neutron separation energy shows a jump at N=20, for instance in the case of Ne isotopes S_{2n} drops significantly with increasing neutron number at ^{24}Ne. In the case of magnesium the neutron drip line of ordinary Mg nucleus is ^{42}Mg with nearly vanishing two-neutron separation energy. As can be seen in the figure, adding one Λ hyperon, the hyperon stabilizes the neutron-rich isotopes and the hypernuclear drip line shifts outward to N=32. For the case of silicon the predicted ordinary neutron drip line nucleus and hyper neutron drip line nucleus are ^{48}Si (N=34) and $^{49}_{\Lambda}Si$ (N=34). In the same way for the chain of sulfur isotopes, ^{54}S and $^{55}_{\Lambda}S$ are the predicted drip line nuclei, respectively. The appearance of the steep drop in the two-neutron separation energy at N=20 and N=32 in the RMF calculation is in agreement with the magic number N=20 and the experimental shell closure at N=32 [13]. In summary, the predicted ordinary neutron drip line and the hypernuclear neutron drip line for Ne, Mg, Si, S and Ar in RMF (NL3*) and chiral model(χ_m) are compared with the experimental values [3] as shown in table 1. We observe that the nuclei defining the nuclear and hypernuclearneutron drip lines have the same neutron numbers in both models except for Mg in the NL3* parameter set. In this case the extra binding arising from adding a Λ leads to the stabilization of a nucleus with two more neutrons. In contrast, according to the results with the chiral model, the neutron drip line does not shift by adding one Λ to the nucleus. Comparing to known binding energies, the parameter set χ_m generates more accurate results in the calculation of the total binding energy for all neutron-rich nuclei near the neutron drip line compared to the RMF approach.

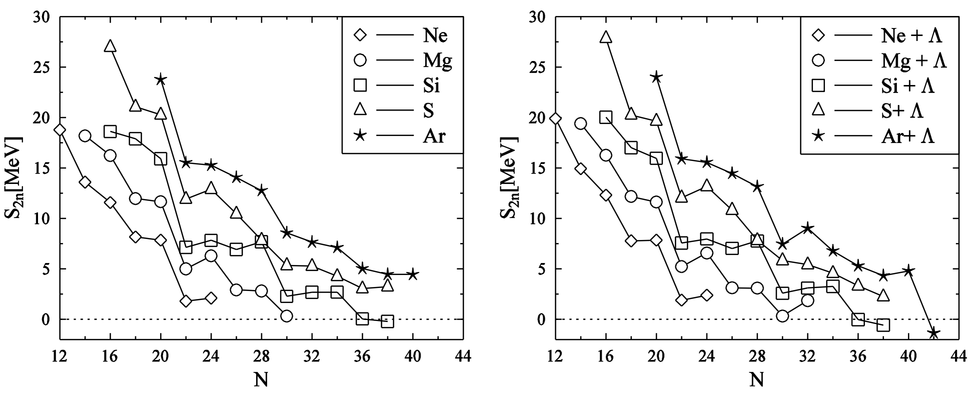

Fig. 1. The two-neutron separtaion energy S_{2n} versus neutron number N for neutron rich Ne-Ar regoin.

4. THE EFFECT OF THE Λ ON NUCLEAR DEFORAMTION

We calculate the axial deformation of ordinary nuclei and one-Λ hypernuclei for neutron-rich isotopes of Ne, Mg, Si, S and Ar. In general, by adding one Λ, both parameter sets χ_m and NL3* show a tendency of reduced nuclear deformation. As a general guideline the results show that deformed nuclei can change into spherically shaped hypernuclei when the difference in energy between the oblate or prolate configuration and the spherical configuration of the original nucleus is less than about 0.25 MeV. For all studied isotopes, in the chiral model the energy difference between oblate or prolate minimum and spherical minimum is at least 2 MeV. Therefore, within this approach we do not observe a substantial change in shape due to the additional Λ. Only in the NL3 and NL3* parameter sets one can observe a change of deformed nuclei into spherically shaped nuclei with the inclusion of one Λ hyperon. In the case of ^{28}Si nucleus, although using the NL3 parameter set the oblately deformed nucleus changes into a spherical hypernucleus, for other parameterizations like NL3* the deformation is reduced only slightly. This general behavior might change by investigating more exotic hypernuclei. For instance, the deformed ^{28}Si nucleus becomes spherical through the addition of two Λ hyperons (NL3*) as shown in the left panel of Fig. 2. For ^{30}Si, ^{32}S and ^{34}Si nuclei, the energy difference between the prolate or oblate configuration and spherical configuration is less than 0.25 MeV and they could be changed into spherical shaped nuclei with the addition of one Λ hyperon. Among these specific four nuclei, only ^{32}S is a prolate nucleus and the other three nuclei are oblate. With the inclusion of one Λ hyperon to the core nucleus ^{32}S, ${}^{33}_{\Lambda}S$ can be transformed to spherical shape as shown in the right panel of Fig. 2.

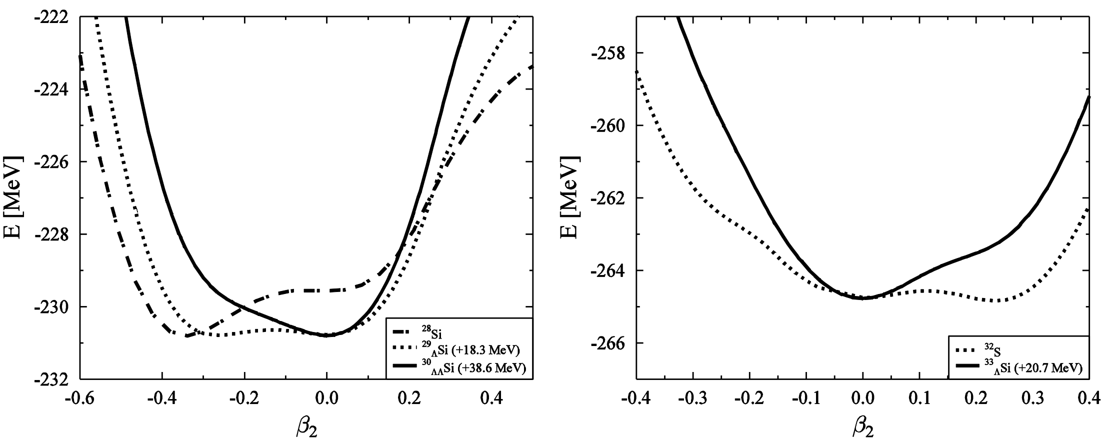

Fig. 2. The potential energy surface for ^{28}Si (dashed line) and ${}^{29}_{\Lambda}Si$ (dotted line) and ${}^{30}_{\Lambda\Lambda}Si$ (solid line) nuclei in RMF theory with NL3* in the left panel. Right panel: same as left panel for ^{32}S and ${}^{33}_{\Lambda}S$.

5. CONCLUSIONS

We have investigated the ground state properties of neutron-rich nuclei for Ne, Mg, Si, S and Ar by using two parameter sets NL3* and χ_m in meson field theories. We predicted the neutron drip line for these nuclei. The χ_m parameter set generates reasonable neutron drip-line nuclei in agreement with currently available data. The effect of including a Λ hyperon has been studied in detail with a variety of parameter sets. In general one can observe small changes of the nuclear deformations. However, within NL3* some deformed nuclei change to spherical hypernuclei by adding a Λ. As an approximate guiding rule it was seen that for energy differences less than 0.25 MeV for different (meta-)stable states of deformed nuclei the corresponding hypernucleus will become spherical. For the models under investigation in this article the inclusion of a Λ hyperon did not significantly affect the position of the neutron drip line for elements ranging from Ne to Ar.

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