Effect of Λ hyperons on the neutron drip line

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"10th International Conference on Hypernuclear and Strange Particle Physics"

September 14th-18th, 2009, "RICOTTI" in Tokai, Ibaraki (Japan)

Motivation

A particular feature of hypernuclear physics that might be experimentally accessible in the future is:

The change of the nuclear structure due to the effect of added hyperons, and, in particular, the modification of states close to the neutron drip line when adding one or more Λ hyperons to the system.

Its study will provide information on the hyperon-nucleon and hyperon-hyperon forces, complementary to that obtained from hypernuclear spectroscopy.

L. Majling, Nucl. Phys. A 585, 211 (1995) & H. Tamura, Eur. Phys. J. A 13, 181 (2002)

The subject has generated some theoretical interest, and several studies of neutron-rich hypernuclei have been performed in different theoretical frameworks

Relativistic mean-field

D. Vretenar, W. Pöschl, G. A. Lalazissis & P.Ring, Phys. Rev. C 57, R1060 (1998).

H. F. Lu, J. Meng, S. Q. Zhang & S.-G. Zhou, Eur. Phys. J. A 17, 19 (2003).

Skyrme-Hartree-Fock

T. Y. Tretyakova & D. E. Lanskoy, Eur. Phys. J. A 5, 391 (1999).

Generalized mass formula

C. Samanta, P.Roy Chowdhury & D. N. Basu, J. Phys. G 35, 065101 (2008).

In this work ...

- We study the effect of Λ hyperons on neutron drip properties in hypernuclear matter and hypernuclei.

- We use a microscopic in-medium ΛN force derived from BHF calculations of hypernuclear matter, combined with recent reliable nucleonic interactions suitable for neutron-rich environments. (Talk of H.-J. Schulze, Monday 14th).

- Hypernuclei are treated in a Skyrme-Hartree-Fock model including quadrupole deformations and nucleonic pairing.

Phys. Rev. C 78, 054306 (2008)

Neutron drip properties in bulk hypernuclear matter

Neutron drip condition:

$$\mu_n = 0$$

Using the usual thermodynamical relations

$$\mu_i = \frac{\partial \varepsilon}{\partial \rho_i}, \qquad i = n, p, \Lambda$$

the n, p, and Λ chemical potential are obtained from the total energy density of the system

$$\varepsilon = \varepsilon_N + \varepsilon_\Lambda$$

where for the nucleonic energy density ε_N we have chosen:

- a standard Skyrme functional with the modern Skyrme forces SkI4 and SLy4, which have been specifically devised with attention to the description of neutron-rich systems.

- a simple analytical functional (Av18+3BF) which parametrizes the variational calculation of Akmal, Pandharipande & Ravenhall (PRC 58, 1804 (1998))

$$\varepsilon_N = \rho_N \left(E_0 u \frac{u - 2 - \delta}{1 + u\delta} + S_0 u^\gamma \alpha^2 \right), \qquad u = \frac{\rho_N}{\rho_0}, \qquad \rho_N = \rho_n + \rho_p$$

with

$$\rho_0 = 0.16\, fm^{-3}, \qquad E_0 = 15.8\, MeV$$

$$S_0 = 32\, MeV, \qquad \gamma = 0.6, \qquad \delta = 0.2$$

and the contribution due to the presence of Λ hyperons is written as

$$\varepsilon_\Lambda = \frac{\tau_\Lambda}{2m_\Lambda} + \varepsilon_{N\Lambda}(\rho_n,\rho_p,\rho_\Lambda) + \left(\frac{m_\Lambda}{m^*_\Lambda(\rho_n,\rho_p,\rho_\Lambda)} - 1\right)\left(\frac{\tau_\Lambda}{2m_\Lambda} - \frac{3}{5}\frac{(3\pi^2)^{2/3}\rho_\Lambda^{5/3}}{2m_\Lambda}\right)$$

with $\varepsilon_{N\Lambda}$ and m_Λ^* fitted to BHF calculations of hyperonic matter (using the NSC89 YN force) in the following way

$$\varepsilon_{N\Lambda} \approx -\left[368 - (1717 + 268\alpha - 920\alpha^2)\rho_N + (2932 - 776\alpha + 2483\alpha^2)\rho_N^2\right]\rho_N\rho_\Lambda$$
$$+ \left[449 - 2470\rho_N + 5834\rho_N^2\right]\rho_N\rho_\Lambda^{5/3}$$

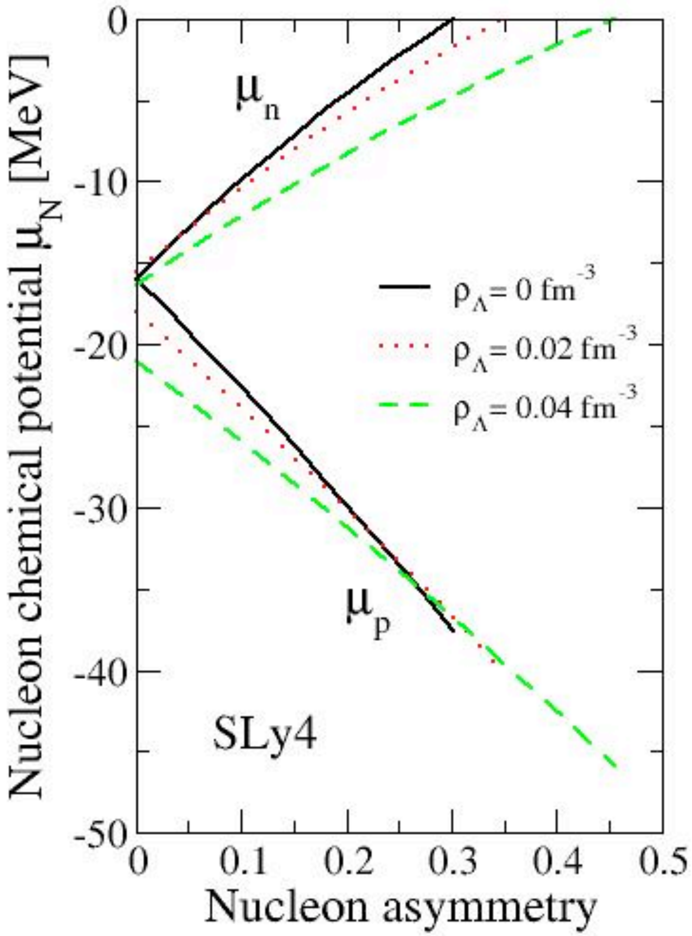
$$\frac{m_\Lambda}{m_\Lambda^*} \approx 1 - \left[1.58 + 0.12\alpha - 0.12\alpha^2 + 0.54y - 0.14y^2\right]\rho_N$$
$$+ \left[4.11 + 2.11\alpha + 2.88\alpha^2 + 0.35y + 1.17y^2\right]\rho_N^2$$
$$- \left[4.03 + 7.08\alpha + 5.18\alpha^2 - 0.93y + 3.27y^2\right]\rho_N^3$$

being

$$\alpha = (\rho_n - \rho_p)/\rho_N$$
$$y = \rho_\Lambda/\rho_N$$

See talk of H.-J. Schulze

Neutron and proton chemical potentials at zero pressure vs. nucleon asymmetry

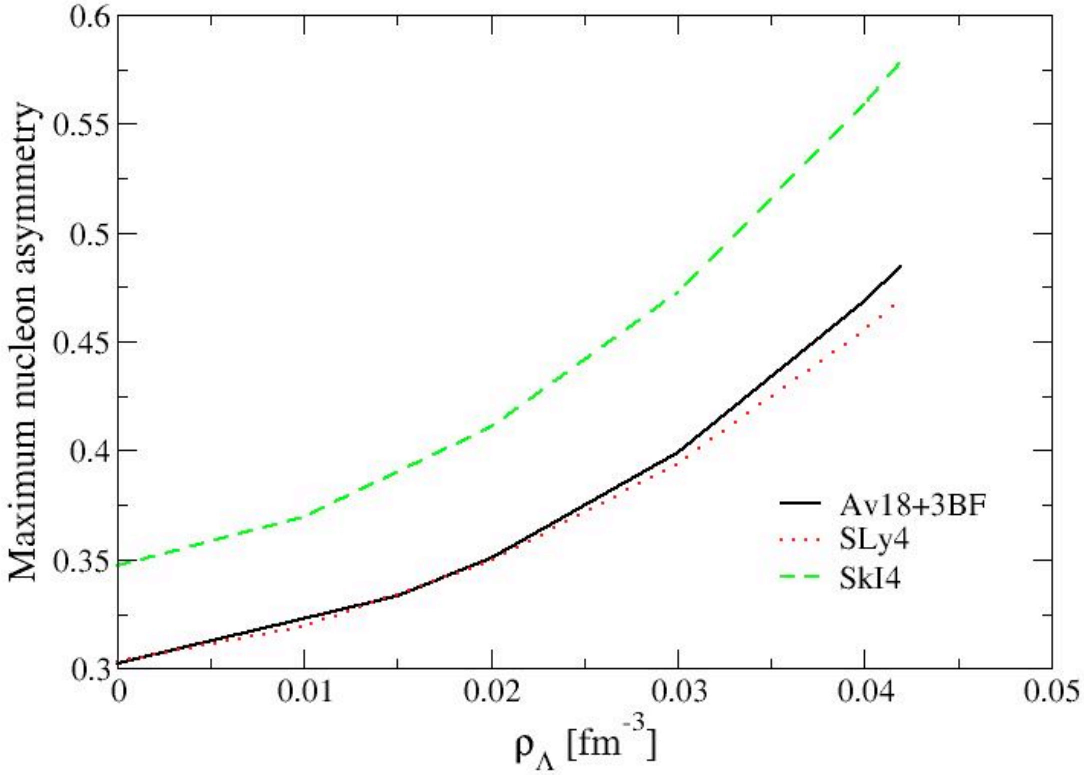


- . As expected μ_p decreases with the nucleon asymmetry whereas μ_n increases.

- The neutron drip point, defined by the condition $\mu_n = 0$, increases with the presence of Λ's which act as an additional source of attraction.

- The presence of Λ's produces a breaking of the isospin symmetry (induced by the underlying NSC89 YN force) even at zero asymmetry.

Maximum nucleon asymmetry as a function of ρ_Λ



One thus expect that for finite nuclei the presence of one or more Λ's should increase the number of neutrons that a nucleus can support.

Neutron drip properties in hypernuclei

From our results on bulk matter …

- It is not easy to make quantitative predictions on how the presence of Λ's will affect the neutron drip line in finite nuclei due to the additional complexity associated with the shell structure, pairing and deformation.

- In order to find appreciable effects we focus on nuclei close to the neutron drip line where the highest (partially) occupied s.p. level is very weakly bound or where additional bound states can be expected with little added attraction. In particular we consider neutron-rich isotopes of beryllium and oxygen.

A few lines on the SHF model before showing our results

The total energy of a hypernucleus is written as

$$E = \int d^3 r \varepsilon(r)$$

with the energy density functional

$$\varepsilon = \varepsilon_N\left(\rho_n, \rho_p, \tau_n, \tau_p, J_n, J_p\right) + \varepsilon_\Lambda\left(\rho_n, \rho_p, \rho_\Lambda, \tau_\Lambda\right)$$

and the one-body densities ρ_q, kinetic densities τ_q and spin-orbit currents J_q (q=n,p,Λ) given by

$$\rho_q = \sum_{i=1}^{N_q} n_q^i \left|\phi_q^i\right|^2, \qquad \tau_q = \sum_{i=1}^{N_q} n_q^i \left|\nabla \phi_q^i\right|^2, \qquad J_q = \sum_{i=1}^{N_q} n_q^i \phi_q^{i*}\left(\nabla \phi_q^i \times \sigma\right)/i$$

ϕ_q^i: s.p. wave functions of the N_q occupied states

n_q^i: occupation probabilities (calculated for n/p considering pairing interactions within a BCS approximation)

Minimizing E one arrives at the SHF Schrödinger equation

$$\left[-\nabla\cdot\frac{1}{2m_q^*(\vec{r})}\nabla+V_q(\vec{r})-i\nabla W_q(\vec{r})\cdot(\nabla\times\sigma)\right]\phi_q^i(\vec{r})=e_q^i\phi_q^i(\vec{r})$$

with the s.p. energies e_q^i and the SHF mean fields

$$V_q=V_q^{SHF}+\frac{\partial\varepsilon_{N\Lambda}}{\partial\rho_q}+\frac{\partial}{\partial\rho_q}\left(\frac{m_\Lambda}{m_\Lambda^*}\right)\left(\frac{\tau_\Lambda}{2m_\Lambda}-\frac{3}{5}\frac{(3\pi^2)^{2/3}}{2m_\Lambda}\rho_\Lambda^{5/3}\right),\qquad q=n,p$$

$$V_\Lambda=\frac{\partial\varepsilon_{N\Lambda}}{\partial\rho_\Lambda}+\frac{\partial}{\partial\rho_\Lambda}\left(\frac{m_\Lambda}{m_\Lambda^*}\right)\left(\frac{\tau_\Lambda}{2m_\Lambda}-\frac{3}{5}\frac{(3\pi^2)^{2/3}}{2m_\Lambda}\rho_\Lambda^{5/3}\right)-\left(\frac{m_\Lambda}{m_\Lambda^*}-1\right)\frac{(3\pi^2\rho_\Lambda)^{2/3}}{2m_\Lambda}$$

The nucleon mean field acquires a correction in the presence of Λ's causing a rearrangement of the nucleonic core of a hypernucleus.

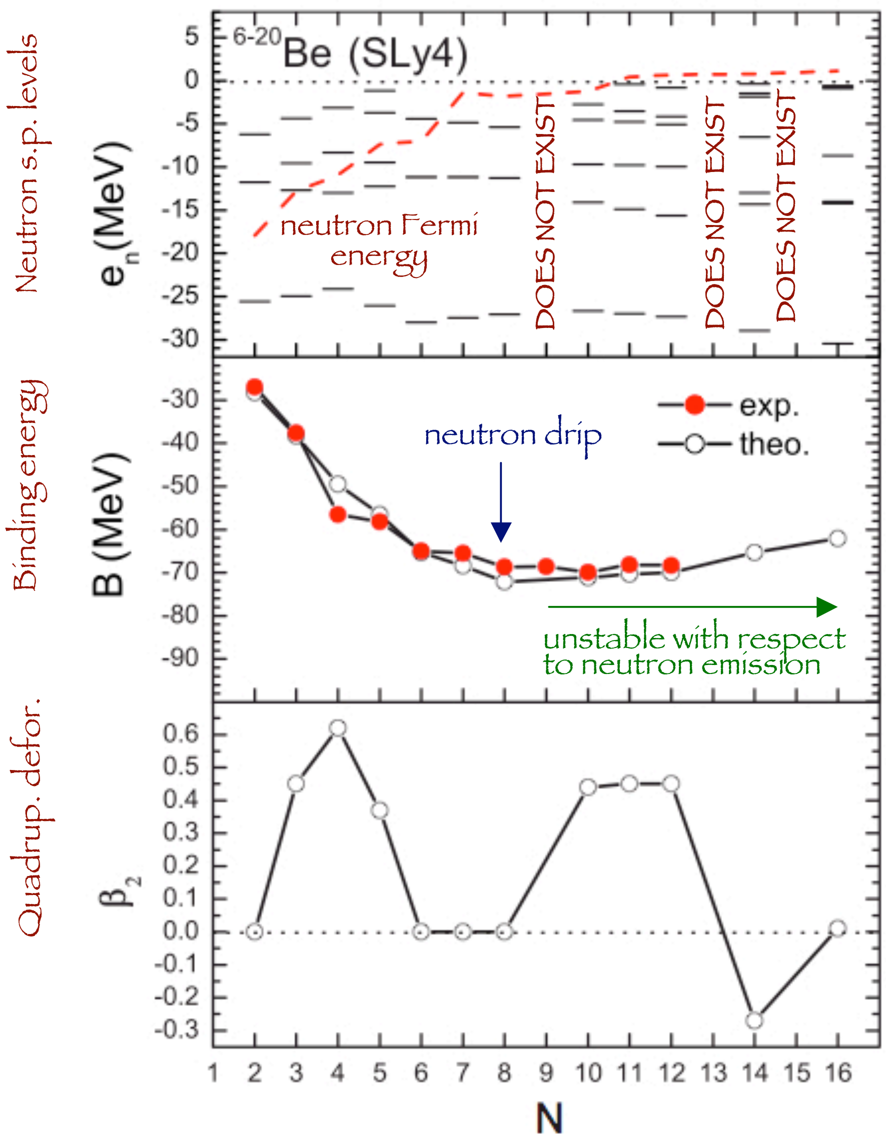
Finally, axial symmetry is assumed for the SHF deformed potentials and the Schrödinger equation is solved in cylindrical coordinates (r,z).

The optical quadrupole deformation parameters

$$\beta_2^{(q)} = \sqrt{\frac{\pi}{5}} \frac{\left(2z^2 - r^2\right)_q}{\left(z^2 + r^2\right)_q}$$

are obtained by minimizing the total energy of the hypernucleus.

Beryllium isotopes



- With the SLy4 force we find Be isotopes with N=1-8,10,11,12, 14,16. Odd nuclei with N=9,13,15 do not exist due to pair breaking.

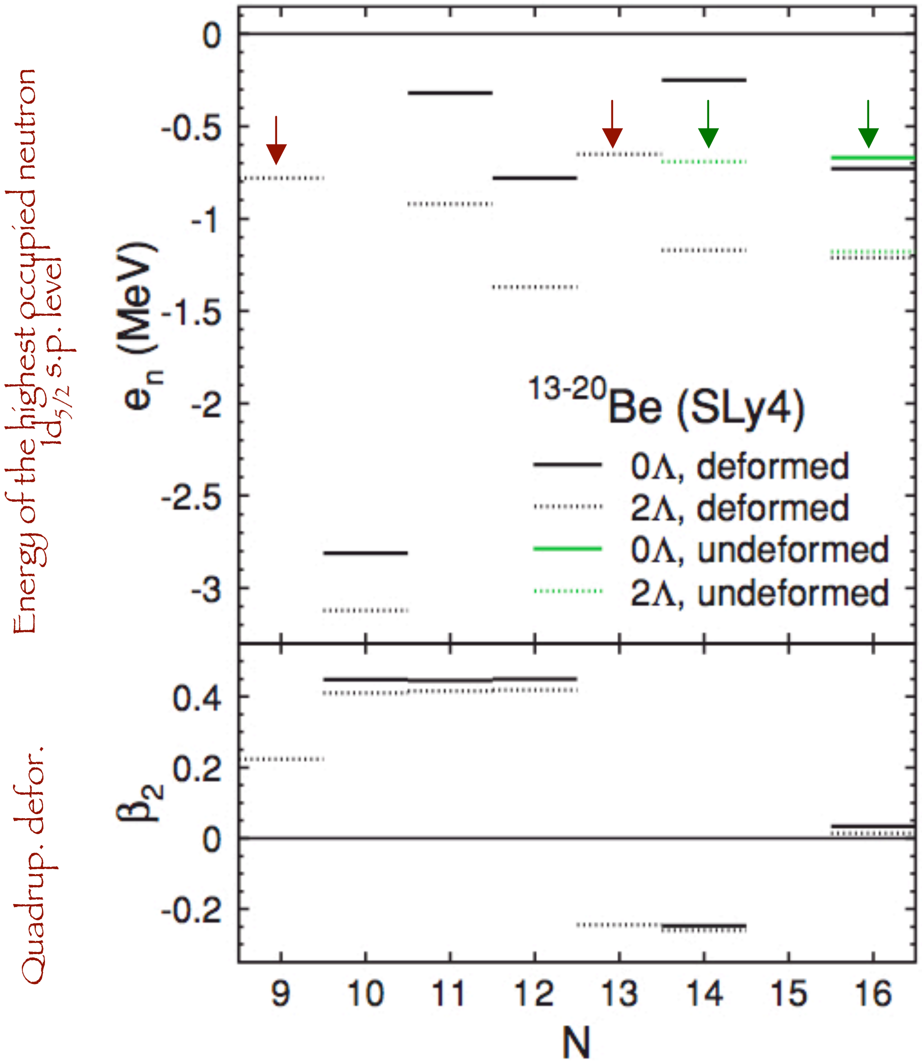
- Neutron drip (minimum of B vs. N) at ^{12}Be.

- Heaviest isotopes extremely unstable due very small binding of the highest occupied levels.

- Isotopes with 8<N<16 only exist due to deformation. N=14 and 16 metastable deformed states.

Important role of deformation & pairing in weakly bound isotopes close to neutron drip.

Effect of added hyperons

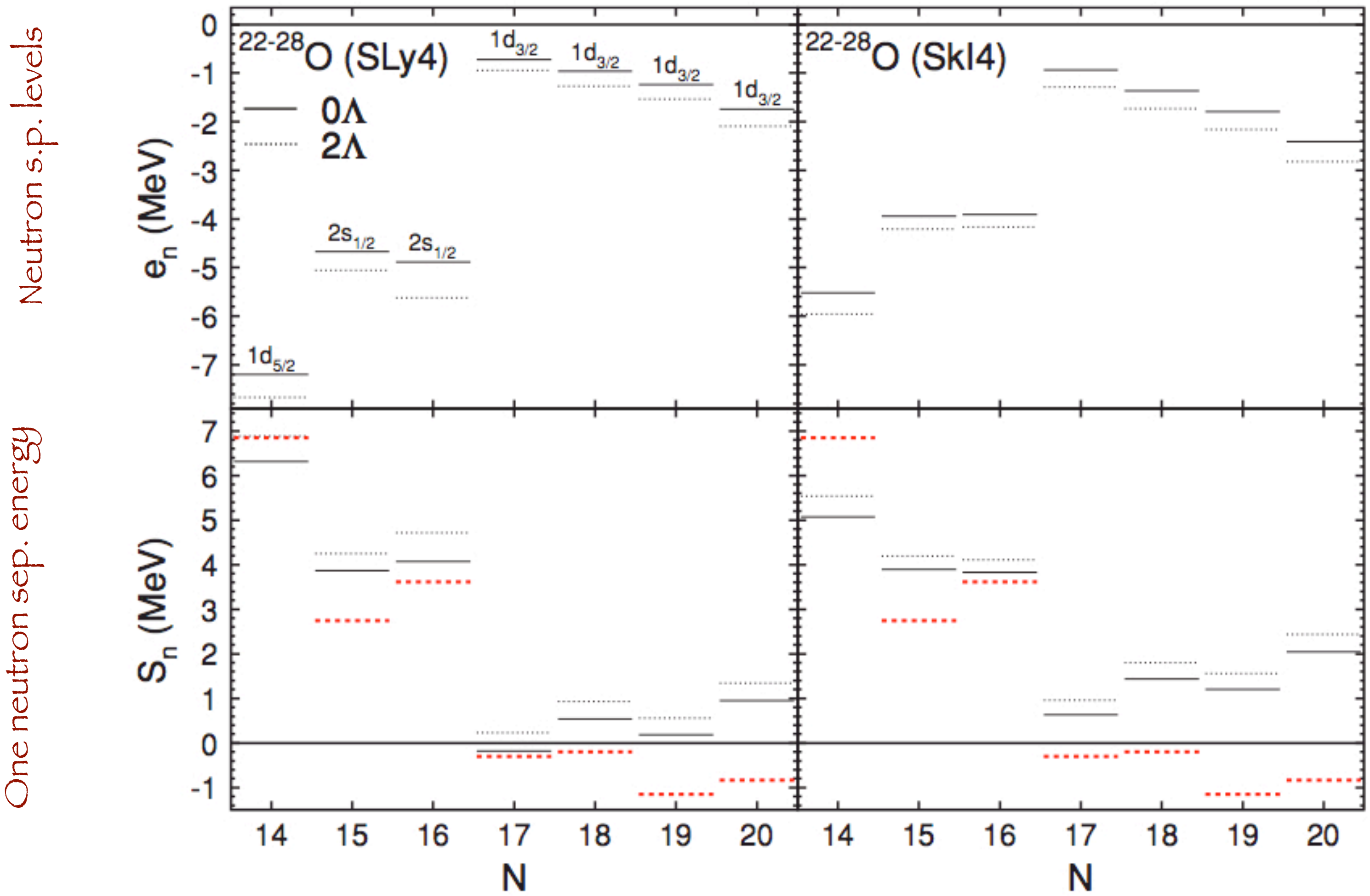


In general the addition of Λ's + deformation increases the neutron binding energies. In particlar:

- Without Λ's & no deformation only isotopes with N=1-8 & 16 exist. The addition of 2Λ's stabilizes also N=14
- Isotopes with N=10,11,12,14,16 exists due to deformation. The addition of 2Λ's augment their binding and allows also N=9,13

Nuclei close to the drip line are stabilized and new isotopes are potentially made available

Oxygen isotopes



There is a strong dependence on the nuclear force but the qualitative effect of added hyperons is the same

Summary & Conclusions

- We have studied the effect of Λ hyperons on neutron drip properties in hypernuclear matter and hypernuclei, using a microscopic ΛN force derived from BHF calculations of hypernuclear matter.

- We have found an extension of the neutron drip line in bulk matter and stabilization of neutron-rich isotopes due to added hyperons.

Obrigado