THE PENINSULAS OF NEUTRON STABILITY OF NUCLEI ON NUCLEAR CHART

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Using HF+BCS method with Skyrme forces we analyze the neutron drip line. It is shown that around magic and new magic numbers the drip line may form stability peninsulas. It is shown the location of these peninsulas does not depend on the choice of Skyrme forces. It is found that the size of the peninsulas is sensitive to the choice of Skyrme forces and the most extended peninsulas appear with the SkI2 set.

One of the major problems in nuclear physics having also interdisciplinary importance is the positioning of the neutron drip line. The microscopic approaches to the study of neutron rich nuclei include the Hartree-Fock-Bogoliubov (HFB) and Hartree-Fock (HF) methods using effective forces, see f. e. [1,5]. The standard theoretical procedure in locating the neutron drip line is to take a stable nucleus and load it with neutrons until it saturates, that is adding extra neutrons makes the isotope undergo the neutron decay there by releasing these extra neutrons. This method, however, implies a simple structure of the drip line, namely, that any straight line on the nuclear chart, which corresponds to a fixed number of protons, crosses the neutron drip line only once. Yet it might happen that the drip line has a more complicated structure. In the vicinity of magic numbers or new magic numbers the following scenario can take place. At some point (N, Z) nuclei lose their stability but then after gaining more neutrons their stability becomes restored. This leads to the formation of stability peninsulas on the nuclear chart.

This scenario of formation of stability peninsulas has been analyzed by us in Refs. [2,3], [6-11] for the isotopes of O, Ar, Ni, Zr, Kr, Pb, Rn and other elements. The calculations were performed using the HF+BCS approach with Skyrme forces accounting for deformations (DEF HF approach).

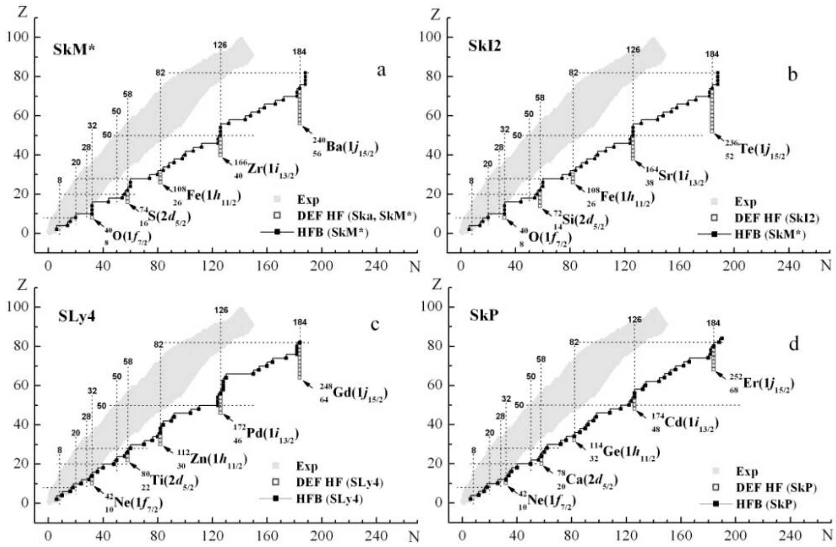

Figure 1. The nuclear chart and the 1n drip line. Filled area shows experimentally known nuclei. The solid line going through the dark squares is the 1n drip line in HFB calculations [5]. Empty squares are nuclei stable against 1 neutron emission according to DEF HF calculations with SkM*(a), SkI2(b), SLy4(c) and SkP(d) forces. The dotted line corresponds to magic numbers N = 8, 20, 28, 50, 82, 126, 184 and to the new magic numbers N=32, 58.

In [6-11] we have analyzed the mechanism, which leads to the stability restoration. It turns out that nuclei lying close to such peninsulas possess low–lying quasi-stable one–particle states. By adding neutrons one makes these levels dive into the discrete spectrum, thus stabilizing the isotope.

The DEF HF calculations are performed using the deformed harmonic oscillator basis, where the basis parameters are optimized on each iteration, for details see [3]. The optimization procedure consists in choosing optimal oscillator frequencies, which minimize the total energy within a given basis.

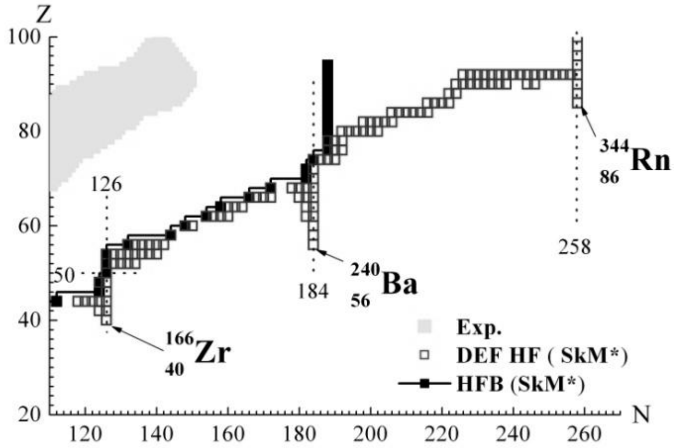

Figure 2. . Fragment of the neutron drip line. The notations repeat that of Fig. 1. One can see the formation of stability peninsulas at N = 184 and N = 258.

Let us mention that the optimization procedure facilitates the calculation and, more important, corrects the basis functions for the spatially extended density distributions near the drip line [3]. The pairing constant is set to $G = (19.5/A)[1 \pm 0.51(N - Z)/A]$, where the plus and minus signs refer to protons and neutrons respectively. In DEF HF calculations we include only bound one particle states. In spite of ignoring the continuum states this method still provides a good agreement with the HFB, see [6–11]. Since all nuclei, which lie on the stability peninsulas are spherical we also use a spherical code (SPH HF), which solves the HF equations directly rather than using a particular basis. In the BCS scheme of the spherical code we implement the inclusion of localized quasibound continuum states.

Stability peninsulas originate for all Skyrme forces, which produce low–lying quasibound one–particle states with high angular momentum (which are responsible for a high centrifugal barrier confining the particles). The observed stability peninsulas with respect to one neutron emission are shown in Fig. 1 for different Skyrme forces. It is easy to see from Fig. 1 that the formation of peninsulas on the neutron drip line happens at the same N values for all forces but peninsula edges have different Z values. We found that Ska and SkM* forces occupy an intermediate position between SkI2 and SkP, in the sense that more elements are stable with SkI2 and less with SkP. The forces SkI2 are the most optimistic, at the same time the formation of stability peninsulas for SkP is rather rare. The difference between two of these forces is depicted in Fig. 1. 1n drip line in Fig. 1 for various Skyrme forces has typical bend points around known magic numbers N =82 (SLy4), N =126 (SkM*, SkI2, SLy4, SkP), N =184 (SkM*, SkI2, SLy4, SkP) and also for N = 32 (SkM*, SkI2, SkP) and N = 58 (SkM*, SkI2, SLy4, SkP). The bend points indicate the stability enhancement around these N–values. It is worth noting that the stability peninsulas are formed for various Skyrme forces around the same neutron numbers. As we have already mentioned the stability restoration results from low–lying quasibound states, which immerse into the bound spectrum for higher N [6–11].

Below we list the stable isotopes that form stability peninsulas and the responsible sub-shells for the Skyrme forces SkM* and Ska. $1f_{7/2}$– ^{40}O; $2d_{5/2}$– ^{76}Ar, ^{74}S; $1h_{11/2}$– ^{110}Ni, ^{108}Fe; $1i_{13/2}$– ^{174}Cd, ^{172}Pd, ^{170}Ru, ^{168}Mo, ^{166}Zr; $1j_{15/2}$– ^{256}Hf, ^{254}Yb, ^{252}Er, ^{250}Dy, ^{248}Gd, ^{246}Sm, ^{244}Nd, ^{242}Ce, ^{240}Ba. From Fig. 1 it can be seen that the stability peninsulas with SkI2 forces are by one or two Z longer than those formed with SkM*. For N = 184 the last stable isotope with SkI2 forces is ^{236}Te having Z = 52, which is close to the magic Z = 50. The neutron to proton ratio in ^{236}Te reaches N/Z =3.54. In the case of ^{40}O one has N/Z =4! For SLy4 and SkP forces the whole neutron drip line becomes shifted in the positive Z direction. The edges of stability peninsulas for SLy4 are formed by the isotopes ^{42}Ne; ^{80}Ti, ^{112}Zn, ^{172}Pd, ^{248}Gd. For SkP forces the edges correspond to ^{42}Ne; ^{78}Ca, ^{114}Ge, ^{174}Cd, ^{252}Er. For all Skyrme forces the nuclei forming stability peninsulas are spherical in DEF HF calculations, which is characteristic of magic numbers. The spherical form allows to run additional check with SPH HF method, where pairing is treated more precisely. The most impressively extended stability peninsulas occur at N = 184, N=256.

Fig. 2 shows the corresponding fragment of the neutron drip line. Here one can also see the stability peninsula at N=258. This magic number was discussed in [4].

Fig. 3 shows one neutron separation energies for the isotone chain N =184 (SkM* forces). One can see that S_n and S_{2n} decrease monotonically. The nucleus ^{240}Ba lies on the edge of stability peninsula, its one neutron separation energy is very small S_n = 0.024 MeV (DEF HF calculation) and S_n=0.064 MeV (SPH HF calculation).

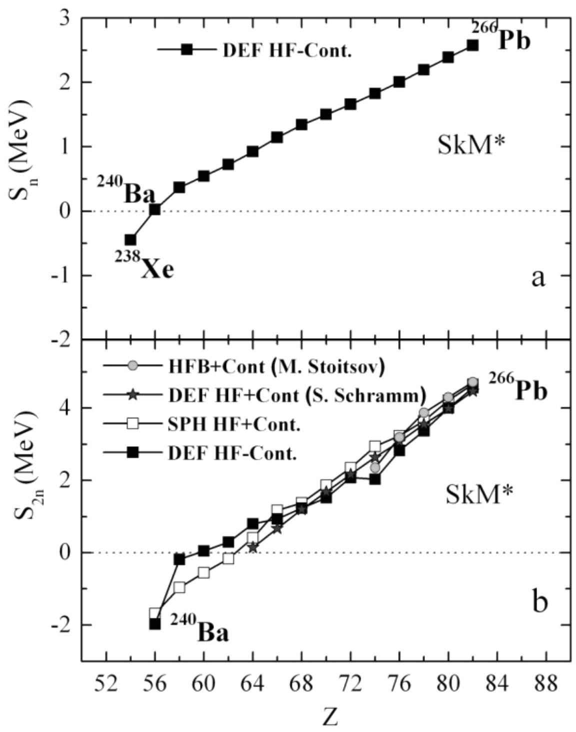

Figure 3. One and two neutron separation energies for the series of isotones corresponding to N = 184 for SkM* forces. (a) One neutron separation energies in DEF HF calculations without continuum states in the BCS scheme. (b) two–neutron separation energies. Dark squares are DEF HF calculations (without continuum in the BCS). Light squares are SPH HF calculations with continuum states. Stars are DEF HF in grid calculations with continuum states. Circles ate HFB calculations [5].

The last filled one–particle level is $1j_{15/2}$, which has the HF potential with the centrifugal barrier height of 8.58 MeV. From Fig. 3 one can see that DEF HF, SPH HF and HFB calculations are in good agreement. The nucleus ^{248}Gd, which has Z = 64 has a positive S_{2n} value. Thus for N = 184 the stability peninsula contains isotopes that are stable against both one and two–neutron emission.

In conclusion, using DEF HF (oscillator basis and grid) and SPH HF approaches with Skyrme forces we show that beyond the conventional theoretically predicted 1n drip line there may exist stability peninsulas, which contain nuclei stable against either 1n or 2n emission or both. The peninsulas are formed at N =32, 58, 82, 126, 184, 258 which are either magic or new magic numbers. This was shown for various choices of Skyrme forces. All isotones with such neutron numbers are spherical. The obtained results indicate that the neutron drip line may have a more complicated structure than it was assumed earlier.

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