PENINSULA OF NEUTRON STABILITY OF NUCLEI IN THE NEIGHBORHOOD OF N=258

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Dual year Russia-Spain
Particle Physics, Nuclear Physics
and Astroparticle Physics
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- **Systematic study of deformed nuclei at the drip lines and beyond**
  

- **Investigation of possibility of existence of islands (peninsulas) of nuclei stable with respect to the emission of one or two neutrons beyond the drip line on the base of HF method with Skyrme forces**
  

**Experiment**


O. B. Tarasov, T. Baumann, A. M. Amthor et al., New isotope $^{44}$Si and systematic of the production cross sections of the most neutron-rich nuclei, Phys. Rev. C 75 (2007) 064613.

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**The condition which defines the position of neutron drip line**

1. $\lambda_n = 0$
2. $S_n = 0$ (1n drip line) $\quad S_{2n} = 0$ (2n drip line)

**Methods** HF, HFB, RMF, FRDM
HF

HF equations:

\[
\left[ -\nabla \frac{\hbar^2}{2m_q^* (\vec{R})} \nabla + U(\vec{R}) + \nabla W(\vec{R}) \cdot (-i)(\nabla \times \vec{\sigma}) \right] \Phi_i = e_i \Phi_i
\]

Axially deformed nuclei (DHF)

\[
\Phi_i (\vec{R}, \sigma, q) = \chi_{q_i} (q) \sum_{\alpha} C^{i}_{\alpha} \varphi_{\alpha} (\vec{R}, \sigma)
\]

\[
\varphi_{n_n, \Lambda} (\vec{R}, \sigma) = \psi^{\Lambda}_{n_r} (r) \psi^{\Lambda}_{n_z} (z) \frac{e^{i\Lambda \varphi}}{\sqrt{2\pi}} \chi_{\Sigma} (\sigma)
\]

\[
\psi^{\Lambda}_{n_z} (z) = N_{n_z} \beta_z^{1/2} e^{-z^2/2} H_{n_z} (z) \quad \xi = z \beta_z \quad N_{n_z} = \left( \frac{1}{\sqrt{\pi} 2^{n_z} n_z !} \right)^{1/2} \quad q = \omega_r / \omega_z
\]

\[
\psi^{\Lambda}_{n_r} (r) = N_{n_r} \beta_{\perp}^{1/2} \sqrt{2} \eta^{1/2} e^{-\eta/2} L^\Lambda_{n_r} (\eta) \quad \eta = r^2 \beta_{\perp}^2 \quad N_{n_r}^{\Lambda} = \left( \frac{n_r !}{(n_r + \Lambda)!} \right)^{1/2} \beta_0 = [m(\omega_r^2 \omega_z)^{1/3}/\hbar]^{1/2}
\]

Spherical symmetry (SHF)

\[
\frac{\hbar^2}{2m_q^*} \left[ -R''_\alpha (r) + \frac{l_\alpha (l_\alpha + 1)}{r^2} R_\alpha (r) \right] - \frac{d}{dr} \left( \frac{\hbar^2}{2m_q^*} \right) R'_\alpha (r) + \{U_q (r) + \frac{1}{r} \frac{d}{dr} \left( \frac{\hbar^2}{2m_q^*} \right) \} [j_\alpha (j_\alpha + 1) - l_\alpha (l_\alpha + 1) - \frac{3}{4}]
\]

\[
\times \frac{1}{r} W_q (r) \right] R_\alpha (r) = e_\alpha R_\alpha (r)
\]

BCS approximation with the paring constant \( G_{n\varphi} = (19.5/A)[1 \pm 0.51(N - Z)/A] \) both for protons and neutrons and only in the space of bound single-particle states for DHF approximation. In SHF approximation we also take into account the single-particle states from continuum.
Blue region shows the atomic nuclei which are experimentally known or extrapolated [A.H. Wapstra]. Red squares show stable nuclei with the respect to emission of one neutron in DHF calculations for Skyrme forces SkM*, Ska (a), SkI2 (b) and SLy4 (c). Solid line and black squares represent 1n drip line (λ_n=0) obtained in the HFB calculations [Stoitsov, Dobaczewski, Nazarewicz, Pittel, PR. C68 (2003) 054312 ] with Skyrme forces SkM*, SLy4 . Dot lines correspond to magic numbers N = 8, 20, 28, 50, 82, 126, 184 and new magic number N=32.

For SkM* 40O N / Z = 4 !
The fragments of neutron single-particle spectra for extremely neutron rich isotopes of oxygen and nickel (SkM*).
The scheme of neutron stability amplification for the isotones at \( N=184 \) which form the edge of stability peninsulas for Ska, SkI2, SkM\(^*\), SLy4 forces. The appearance of peninsulas of neutron stable isotopes beyond the drip line is due to the complete filling of the corresponding neutron subshells with large values of orbital moment which are located in the continuum when they are partially filled and they descend to the discrete spectrum of the bound states with increase of the degree of filling.

HF potentials of the last filled level of the isotones with \( N=184 \) obtained at Ska, SkI2, SkM\(^*\), SLy4 forces in SHF approximation and corresponding to these potentials single particle levels. Red lines show the last filled level.
Dependence of mass quadrupole-deformation parameters $\beta$ of gadolinium isotopes on $A$ for SkM* forces in comparison with the results of the calculations based on the HFB, RMF, FRDM. Empty circles show unstable isotopes.
NZ – chart of the nuclides. Blue region shows the atomic nuclei which are experimentally known. Red squares show stable nuclei with the respect to emission of one neutron in DHF calculations for Skyrme forces SkM*. Dot lines correspond to magic numbers 126, 184, 258. Solid line and black squares represent 1n drip line ($\lambda_n=0$) obtained in the HFB calculations [Stoitsov et al., PR. C68 (2003) 054312] with forces SkM*. For SkI2 forces the edge of peninsula forms $^{328}$Yb.
Properties of neutron rich isotopes of Ra in dependence on mass number $A$ for forces SkM* calculated by DHF method and HFB method [Stoitsov et al., PR. C68 (2003) 054312] :

- $E$ – total energies of nuclei;
- $S_{2n}$ – two neutrons separation energies;
- $S_n$ – one neutron separation energies.

Dot lines correspond to magic numbers $N=126,184,258$. 

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Properties of neutron rich isotopes of U in dependence on mass number A for forces SkM* calculated by DHF method and HFB method [Stoitsov et al., PR. C68 (2003) 054312]:

- $E$ – total energies of nuclei;
- $S_{2n}$ – two neutrons separation energies;
- $S_n$ – one neutron separation energies;
- $\lambda_n$ – neutron chemical potentials.

Dot lines correspond to magic numbers $N = 126, 184, 258$. 

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Dependence of mass quadrupole-deformation parameters $\beta$ for Ra and U isotopes on $A$ for SkM* forces in comparison with the results of the calculations based on the HFB method [PR. C68 (2003) 054312].
Dependence of neutron and proton root-mean-square radii for Ra and U isotopes on A for SkM* forces in comparison with the results of the calculations based on the HFB method [PR. C68 (2003) 054312].
summary

• We calculated the properties of nuclei with extreme neutron excess at \( Z \geq 70 \) including the region of transuranium elements beyond the theoretically known neutron drip line (NDL). The calculations are based on the Hartree–Fock method with Skyrme forces (SkM*, SkI2, SLy4, Ska) taking into account axial deformation and the BCS pairing approximation. It is shown that the isotone chain at the neutron number \( N = 258 \) beyond the NDL forms the peninsula of nuclei stable to emission of one neutron.

• All the isotones with \( N = 258 \) belonging to the peninsula of stable nuclei have spherical proton and neutron density distributions.

• Restoration of neutron stability of isotopes beyond the neutron drip line is connected with the complete filling of the corresponding neutron subshells with large values of orbital moment. Such states have high centrifugal barrier and with incomplete filling of these state they are quasibounded. When the number of neutrons in isotopes beyond the neutron drip line grows some states with large values of orbital moment descend into the region of discrete bounded states. It causes the restoration of nuclei stability with the respect to neutron emission.

• It is shown that neutron drip line can be rather complicate. It is connected with manifestations of shell structure of nuclei and the neutron drip line can extend much further then it was usually supposed before .

• Peninsula of stability with \( N = 258 \) increases the number of the peninsulas of stability which we found before. Within the limits of the used method it has been shown that the proposed mechanism of stability restoration beyond the drip line while adding neutrons to nuclei can have common character and the existence of islands (peninsulas) can be a widespread phenomenon.