Nuclear properties at neutron-rich region

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Introduction

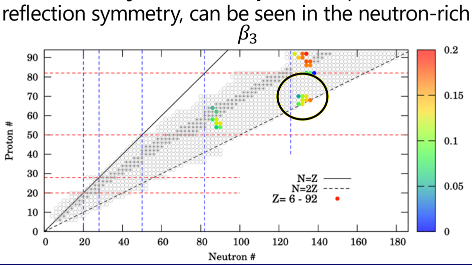
The importance of the neutron-rich environment

Neutron stars : They are composed of enormous neutrons.
Nucleosynthesis : In r-process, neutron-rich environment is crucial.
Drip line : The number of neutrons bound in nuclei is limited.

➡ The neutron-rich region in the nuclear chart is discussed in this poster.

The relevant topic in the region

Reflection-asymmetric shapes : Octupole deformation, which breaks the reflection symmetry, can be seen in the neutron-rich region.



Calculated with 3D Skyrme HF+BCS model

$\beta_3 \equiv (\sum_{m=-3}^{3} \alpha_{3m}^2)^{\frac{1}{2}}$

$\alpha_{3m} \equiv \frac{4\pi}{5}\sqrt{\frac{3A}{5}}\frac{1}{R_{rms}^3}\int dr\, r^3 X_{3m}(\Omega)\rho(r)$

$X_{30} = Y_{30}$

$X_{3m} = (Y_{3-|m|} + Y_{3-|m|}^*)/\sqrt{2}$

$X_{3-m} = -i(Y_{3-|m|} + Y_{3-|m|}^*)/\sqrt{2}$

Shuichiro Ebata and Takashi Nakatsukasa *Phys. Scr.* **92** 064005 (2017)

Method

Self-consistently solving HFB equation

①
$$\begin{pmatrix} e+\Gamma-\lambda & \Delta \\ -\Delta^* & -(e+\Gamma)^*+\lambda \end{pmatrix}\begin{pmatrix} U_k \\ V_k \end{pmatrix} = E_k \begin{pmatrix} U_k \\ V_k \end{pmatrix}$$

$$E[\rho,\kappa] = E[U,V] = Tr\left[\left(e+\frac{1}{2}\Gamma\right)\rho\right] - \frac{1}{2}\mathrm{Tr}[\Delta\kappa^*]$$

② $|\Phi\rangle$ can be composed with new U,V obtained in ①

$$\Delta_{n_1n_2} = \sum_{n_3n_4} v_{n_1n_2n_3n_4}\kappa_{n_3n_4}$$

$$\Gamma_{n_1n_3} = \sum_{n_2n_4} v_{n_1n_2n_3n_4}\rho_{n_4n_2}$$

$$\kappa_{nn'} = \langle\Phi|c_{n'}c_n|\Phi\rangle = (V^*U^T)_{nn'}$$

$$\rho_{nn'} = \langle\Phi|c_{n'}^\dagger c_n|\Phi\rangle = (V^*V^T)_{nn'}$$

$$\lambda_{n,p} = \frac{\partial E}{\partial N} \text{ or } \frac{\partial E}{\partial Z}$$

e : single-particle kinetic energy
v : two-body interaction

Definition of multipole moment

$$\hat{Q}_\lambda = r^\lambda\sqrt{\frac{2\lambda+1}{4\pi}}P_\lambda(cos\theta)$$

$$\beta_2 = \frac{\sqrt{\pi}}{5}Q_2/AR_{rms}^2$$

$$\beta_3 = \sqrt{\frac{3A}{5}}\frac{4\pi}{5}Q_3/R_{rms}^3$$

Canonical single-particle energy: e'

$$e' = \langle\phi|e+\Gamma|\phi\rangle$$

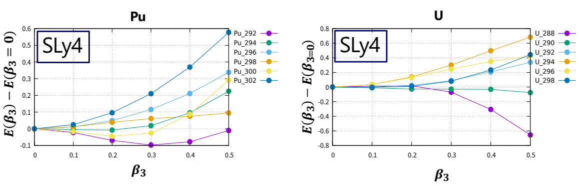
ϕ: a basis that orthogonalizes the density matrix

Condition for bound nuclei

$$S_{2n} = E(Z,N-2) - E(Z,N) > 0$$
$$S_{2p} = E(Z-2,N) - E(Z,N) > 0$$

Result

Potential energy as a function of β_3 by constrained HFB calculation



	N	β_2
Pu(292)	198	0.232792
Pu(294)	200	0.243355
Pu(296)	202	0.252684
Pu(298)	204	0.258106
Pu(300)	206	0.263947
Pu(302)	208	0.266070

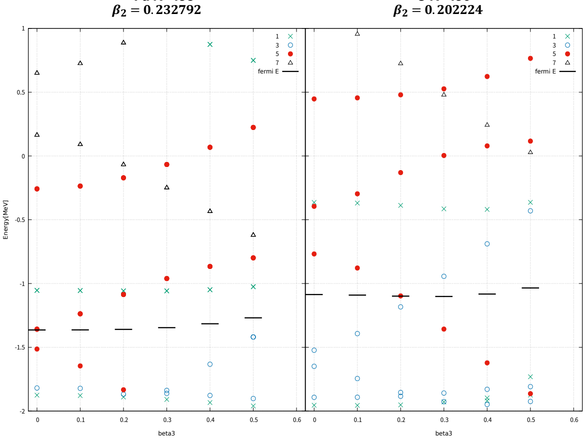
	N	β_2
U(288)	196	0.202224
U(290)	198	0.219507
U(292)	200	0.235291
U(294)	202	0.250783
U(296)	204	0.254231
U(298)	206	0.258710

β_2 are chosen as the value of the ground states obtained by HFB calculation with reflection-symmetry.

Neutron single-particle levels

Labels take the form of $2\Omega[N, n_z, n_r]$ where $\Omega^\pi[N, n_z, n_r]$ is Nillson label.

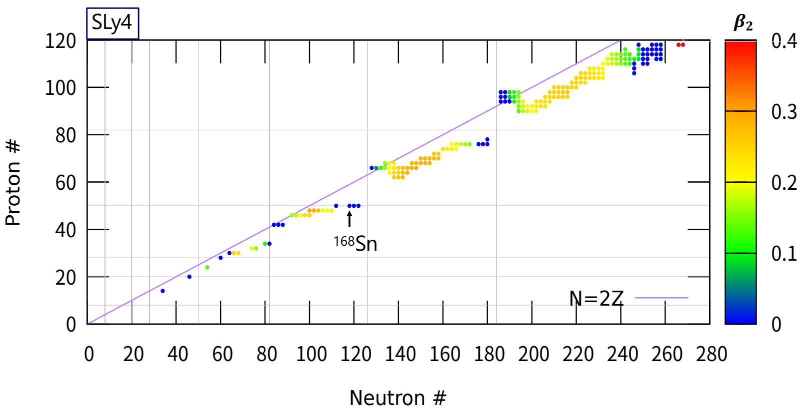
^{292}Pu N=198 $\beta_2 = 0.232792$ | ^{288}U N=196 $\beta_2 = 0.202224$



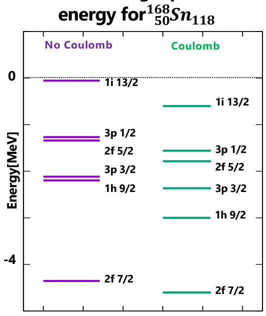
In the region where $E(\beta_3) - E(\beta_3 = 0) < 0$, energy gaps exist between neutron levels near the Fermi surface.

Neutron drip line and the Coulomb interaction

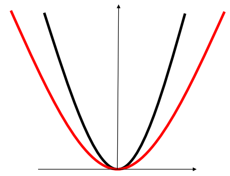
Nuclei that are bound **only in the presence of the Coulomb interaction.**



Neutron single particle energy for $^{168}_{50}Sn_{118}$



Corresponding of the density distribution to the single particle energy.



$V_{h.o.} = \frac{1}{2}M\omega^2x^2$
$E_n = \hbar\omega(n + 1/2)$

The Coulomb interaction expands the density distribution

⬇

Neutron single-particle energies go **DOWN**

⬇

Drip line shifts to neutron-rich region

Conclusion

At neutron-rich region, ^{292}Pu, ^{294}Pu and ^{300}Pu have energy minima as at finite values of octupole deformation.

Neutron drip line can be extended towards neutron-rich region due to the changes in the neutron-single particle energies caused by the Coulomb interaction.

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