Axially symmetric Skyrme-HFB calculation for neutron-rich nuclei

Methods of many-body systems :
mean-field theories and beyond

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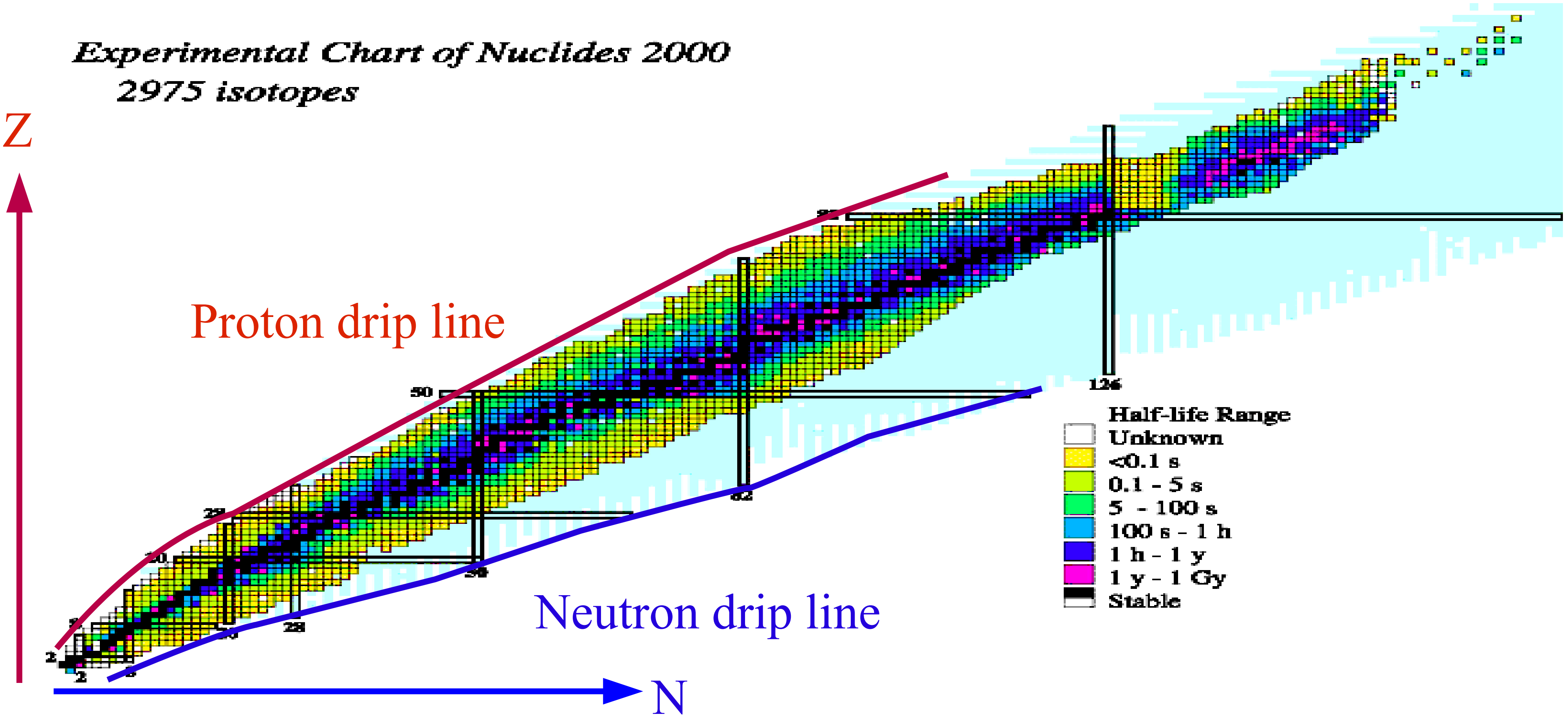
Introduction

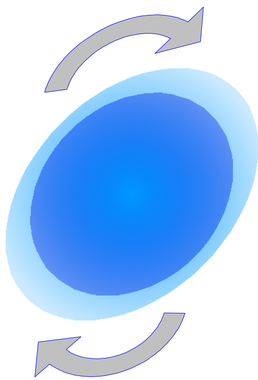


Number of observed unstable nuclei is about 3000.

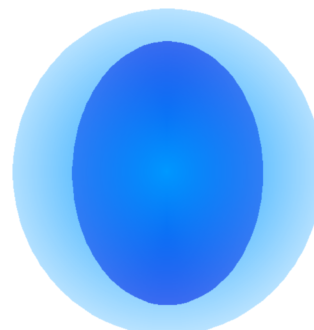
→ Many of them will be deformed !!

- Deformed unstable nuclei are interesting

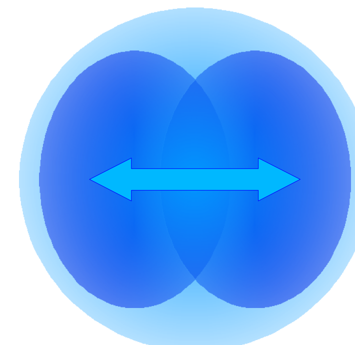
→ **Possibility of finding new phenomena**



Rotational band



Deformed halo & skin



Soft excitation mode

- Possibility of new region of deformation

e.g. Cr isotopes in neutron-rich region
may be a new region of deformation.

→ It is interesting to explore the possibility of static deformation by mean of the mean-field theory.

We adopt axially symmetric Skyrme-HFB theory using the cylindrical coordinate space.

		Deformation	Pairing	unstable nuclei (continuum)	
1972	Vautherin et al.	△	△	×	Deformed Skyrme-HF + BCS
1977	Hoodbhoy et al.	△	△	×	cylindrical coordinate
1984	Dobaczewski et al.	×	○	○	Skyrme-HFB (spherical)
1986	Bonche et al.	○	△	×	3D-cartesian mesh
1994	Gall et al.	○	○	△	3D-cartesian mesh HFB (two basis)
2000	Stoitsov et al.	△	○	○	Axially symmetric HFB (THO)
2003	Teran et al.	△	○	○	Axially symmetric HFB (B-Spline)
	Present work	△	○	○⇒◎	cylindrical coordinate space HFB (2D mesh)

Purpose of the present work.

- **We develop a new code for axially symmetric Skyrme-HFB using the cylindrical coordinate 2D mesh.**

- **We apply the new code to an analysis of the neutron-rich Cr isotopes.**

Theory HFB theory in coordinate space

Total energy ⇒ density and pairing density functional.

$$E\left(\rho(\vec{r}),\kappa(\vec{r})\right)$$

Density $\rho(\vec{r})=\langle\phi_\uparrow^\dagger(\vec{r})\phi_\downarrow(\vec{r})\rangle$

Pairing density $\kappa(\vec{r})=\langle\phi_\uparrow^\dagger(\vec{r})\phi_\downarrow^\dagger(\vec{r})\rangle$

Minimize the total energy by variational method.

$$\delta E\left(\rho(\vec{r}),\kappa(\vec{r})\right)=0$$

Coordinate space HFB equation

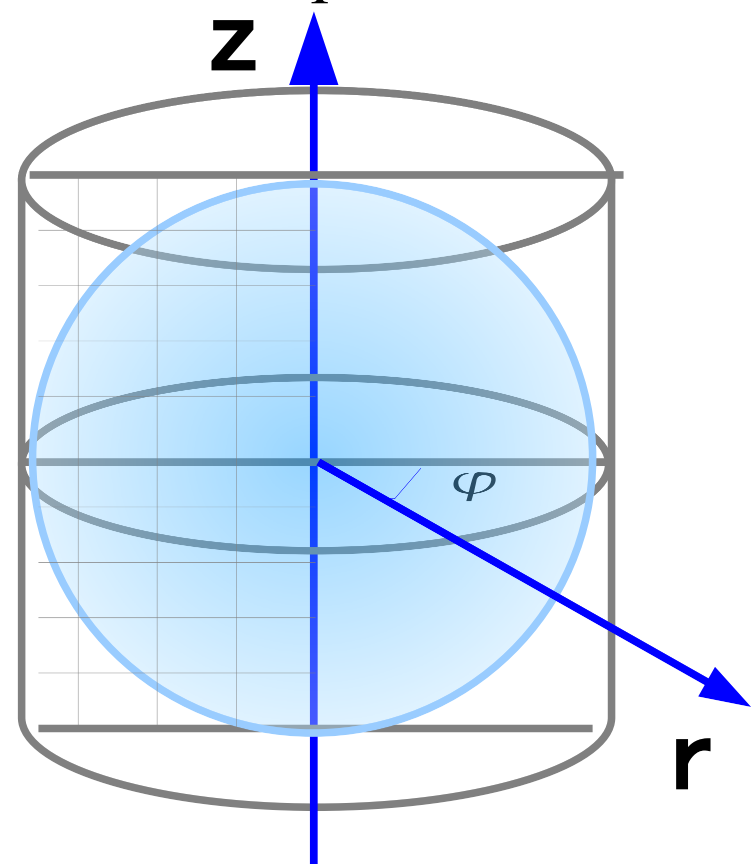
$$\begin{pmatrix} h(\vec{r})-\lambda & \Delta(\vec{r}) \\ -\Delta^*(\vec{r}) & -\left(h(\vec{r})-\lambda\right)^* \end{pmatrix}\begin{pmatrix} \psi_m^{(1)}(\vec{r}) \\ \psi_m^{(2)}(\vec{r}) \end{pmatrix}=E_m\begin{pmatrix} \psi_m^{(1)}(\vec{r}) \\ \psi_m^{(2)}(\vec{r}) \end{pmatrix}$$

HFB equation in cylindrical coordinate

Axially symmetric system

→ Cylindrical coordinate

2D mesh representation



$$\begin{pmatrix} \psi^{(1)}_{n,\Omega}(r,z,\varphi) \\ \psi^{(2)}_{n,\Omega}(r,z,\varphi) \end{pmatrix} = \frac{1}{\sqrt{2\pi}} \begin{pmatrix} e^{i(\Omega-1/2)\varphi}\phi^{(1)}_{n,\Omega}(r,z,\uparrow) \\ e^{i(\Omega+1/2)\varphi}\phi^{(1)}_{n,\Omega}(r,z,\downarrow) \\ e^{i(\Omega-1/2)\varphi}\phi^{(2)}_{n,\Omega}(r,z,\uparrow) \\ e^{i(\Omega+1/2)\varphi}\phi^{(2)}_{n,\Omega}(r,z,\downarrow) \end{pmatrix}$$

$$\begin{pmatrix} h_{\uparrow\uparrow}(r,z)-\lambda & h_{\uparrow\downarrow}(r,z) & \Delta_{\uparrow\uparrow}(r,z) & \Delta_{\uparrow\downarrow}(r,z) \\ h_{\downarrow\uparrow}(r,z) & h_{\downarrow\downarrow}(r,z)-\lambda & \Delta_{\downarrow\uparrow}(r,z) & \Delta_{\downarrow\downarrow}(r,z) \\ \Delta_{\uparrow\uparrow}(r,z) & \Delta_{\uparrow\downarrow}(r,z) & -h_{\uparrow\uparrow}(r,z)+\lambda & -h_{\uparrow\downarrow}(r,z) \\ \Delta_{\downarrow\uparrow}(r,z) & \Delta_{\downarrow\downarrow}(r,z) & -h_{\downarrow\uparrow}(r,z) & -h_{\downarrow\downarrow}(r,z)+\lambda \end{pmatrix} \begin{pmatrix} \phi^{(1)}_{n,\Omega}(r,z,\uparrow) \\ \phi^{(1)}_{n,\Omega}(r,z,\downarrow) \\ \phi^{(2)}_{n,\Omega}(r,z,\uparrow) \\ \phi^{(2)}_{n,\Omega}(r,z,\downarrow) \end{pmatrix} = E_{n,\Omega} \begin{pmatrix} \phi^{(1)}_{n,\Omega}(r,z,\uparrow) \\ \phi^{(1)}_{n,\Omega}(r,z,\downarrow) \\ \phi^{(2)}_{n,\Omega}(r,z,\uparrow) \\ \phi^{(2)}_{n,\Omega}(r,z,\downarrow) \end{pmatrix}$$

Diagonalize the Hamiltonian represented by 2D mesh.

Effective interaction

ph-channel

→ Skyrme interaction (SLy4 parameter set)

+ Coulomb interaction

pp-channel

→ volume type pairing

(ρ-independent δ-interaction)

$$V(\vec{r}_i, \vec{r}_j) = \frac{V_0}{2}\delta(\vec{r}_i - \vec{r}_j)$$

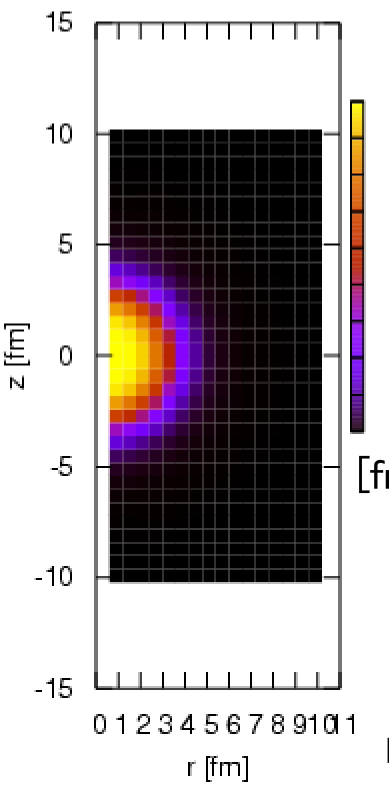
Comparison with the spherical code (Dobaczewski et al.)

Test calculation ^{22}O

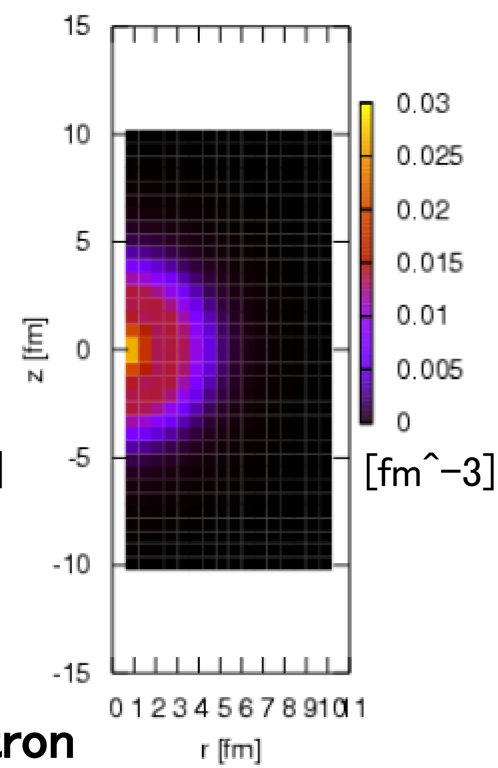
Present work	total binding energy $=-164.131$ [MeV] $\lambda_n=-5.31$ [MeV] $\lambda_p=-18.4$ [MeV] $\Delta_n=1.34$ [MeV] $\Delta_p=0.0$ [MeV]

Result of Spherical code by Dobaczewski et al.	total binding energy $=-164.60$ [MeV] $\lambda_n=-5.26$ [MeV] $\lambda_p=-18.88$ [MeV] $\Delta_n=1.42$ [MeV] $\Delta_p=0.0$ [MeV]

normal density

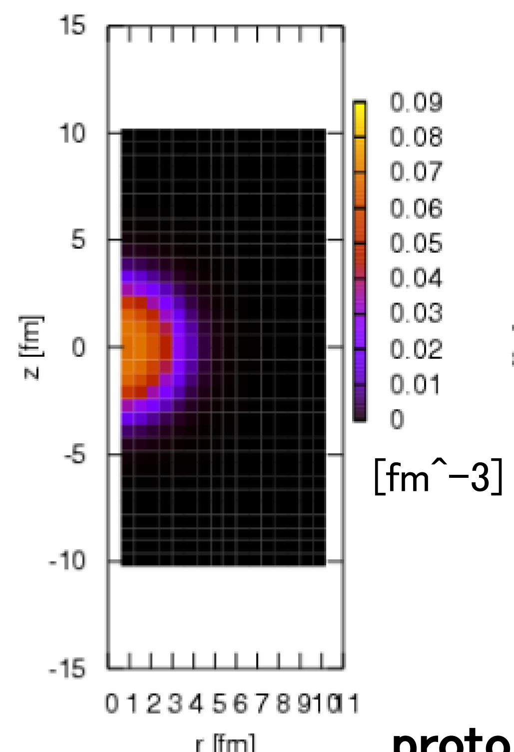


pairing density

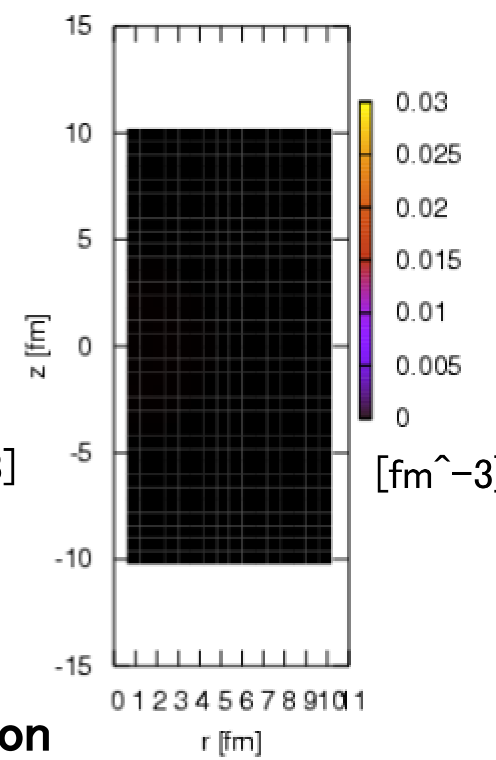


neutron

normal density



pairing density



proton

Comparison with the deformed code (Teran et al.)

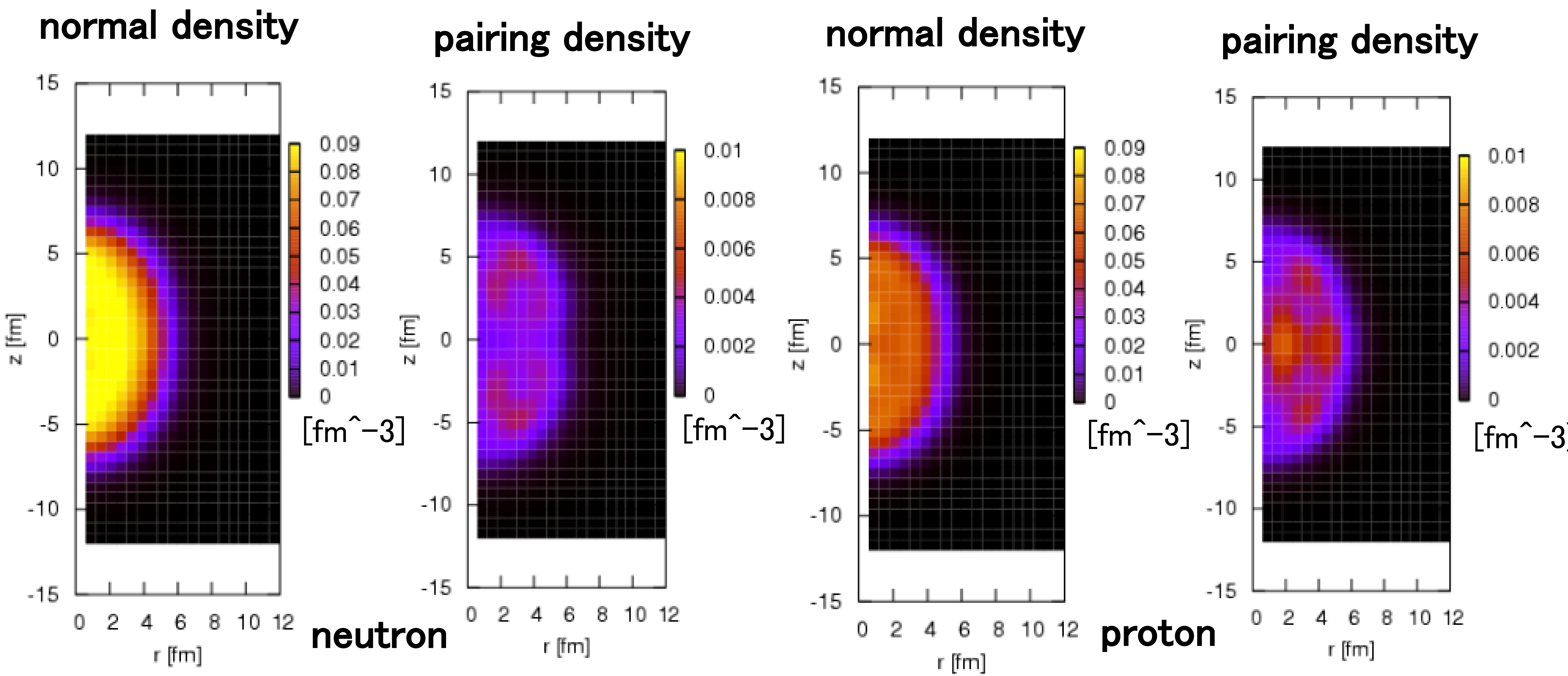
Test calculation ^{102}Zr

Present work

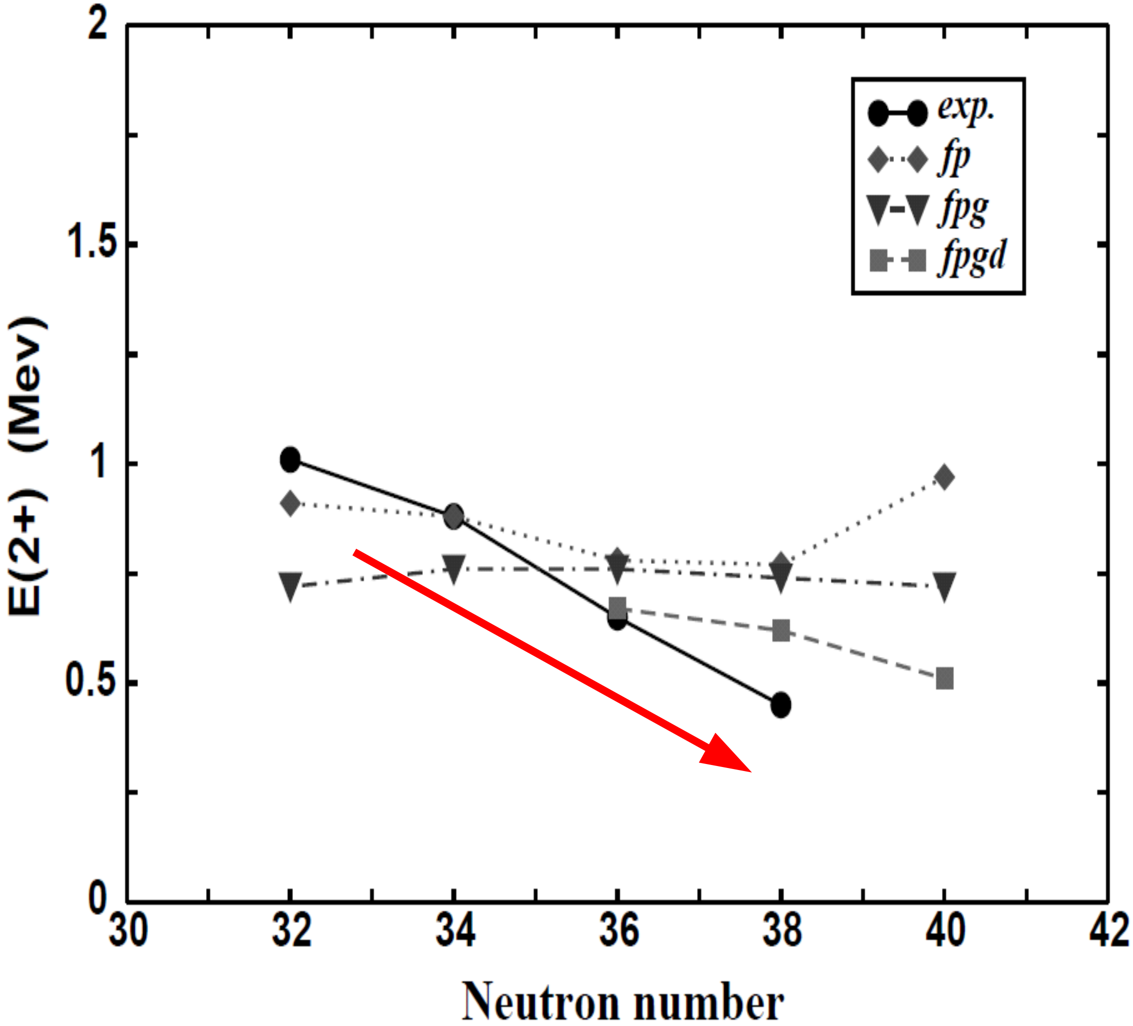
$$\text{total binding energy} = -859.35 \ [\text{MeV}]$$
$$\lambda_n = -5.51 \ [\text{MeV}] \quad \lambda_p = -12.0 \ [\text{MeV}]$$
$$\Delta_n = 0.27 \ [\text{MeV}] \quad \Delta_p = 0.34 \ [\text{MeV}]$$

Redult of Deformed code by Teran et al.

$$\text{total binding energy} = -859.61 \ [\text{MeV}]$$
$$\lambda_n = -5.46 \ [\text{MeV}] \quad \lambda_p = -12.0 \ [\text{MeV}]$$
$$\Delta_n = 0.31 \ [\text{MeV}] \quad \Delta_p = 0.34 \ [\text{MeV}]$$



Application to new deformed region (Cr isotopes).

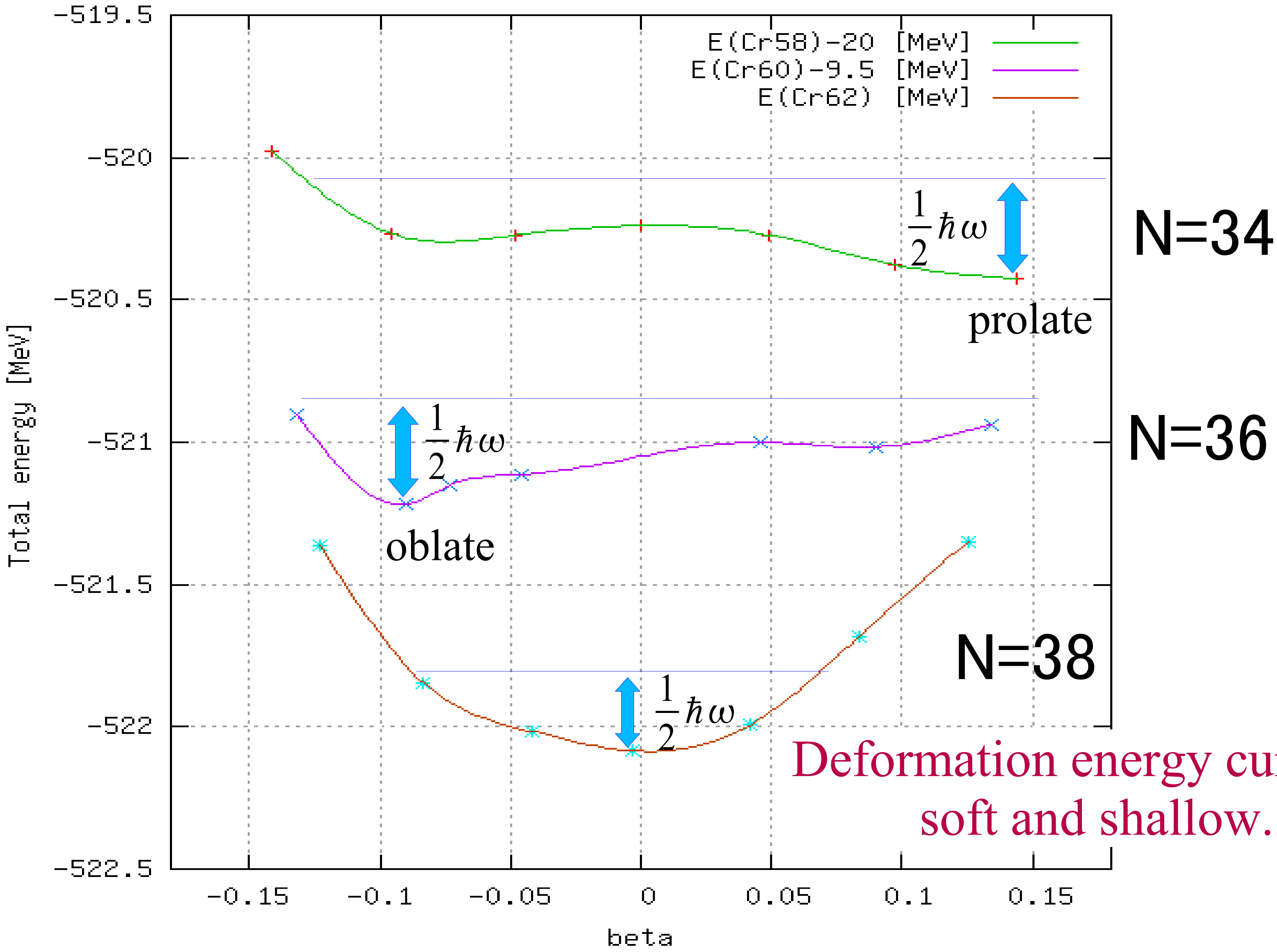


The observation of 2^+ energy
Sorlin et al.
Eur.Phys.J.A16.55(2003)

cf. a new RIKEN experiment on B(E2) in this region by Aoi et al.

→ This may indicate a new deformed region.

Quadrupole deformation energy curve of Cr isotopes



Deformation energy curve is soft and shallow.

Conclusions

- We have developed a new Skyrme-HFB code using cylindrical coodinate 2D mesh.

⇒ Numerical accuracy is checked for ^{22}O and ^{102}Zr.

- We have analyzed deformation energy of neutron-rich Cr isotopes.

⇒ The quadrupole deformation energy curve is soft and shallow.

2^+ excitation mode