High-spin torus isomer state of ^{40}Ca

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Rotation about the symmetry axis

Equator part is expanded due to the centrifugal force

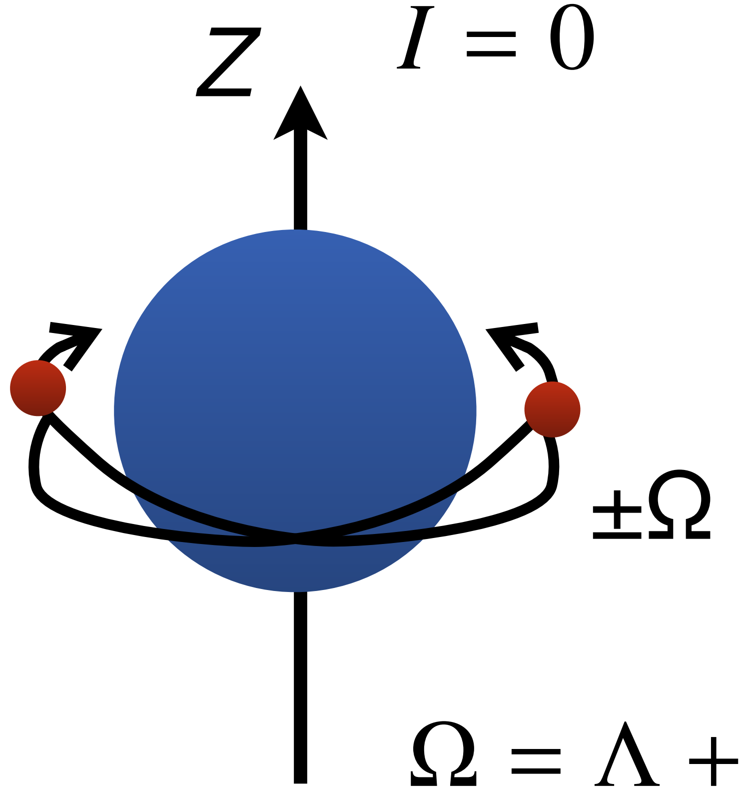
→Moment of inertia increases

Example: The earth

Rotation about symmetry axis is quantum-mechanically forbidden

Spin alignments

$$I = 0$$

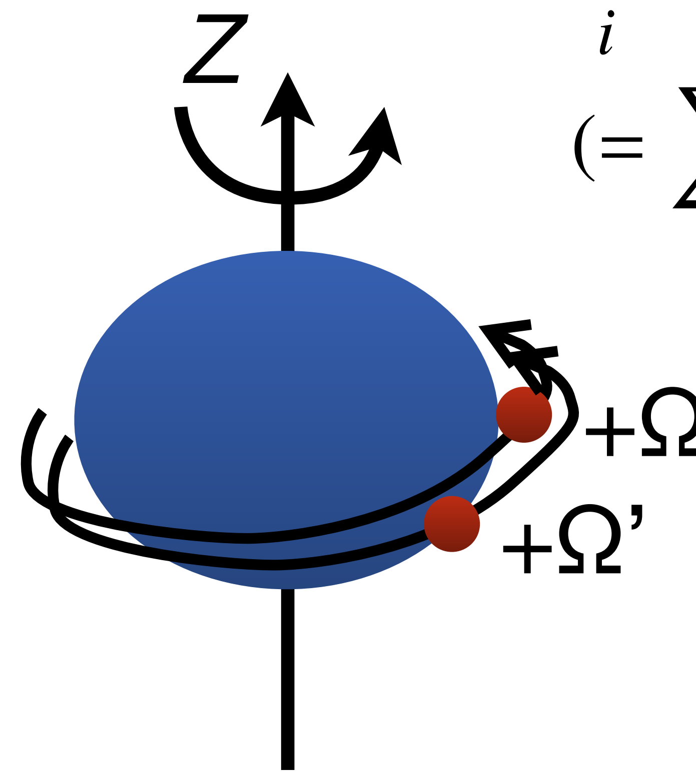


$$\Omega = \Lambda + \Sigma$$

$$(m = \ell_z + \sigma_z)$$

$$I = \sum_i \Omega_i$$

$$(= \sum_i m_i)$$

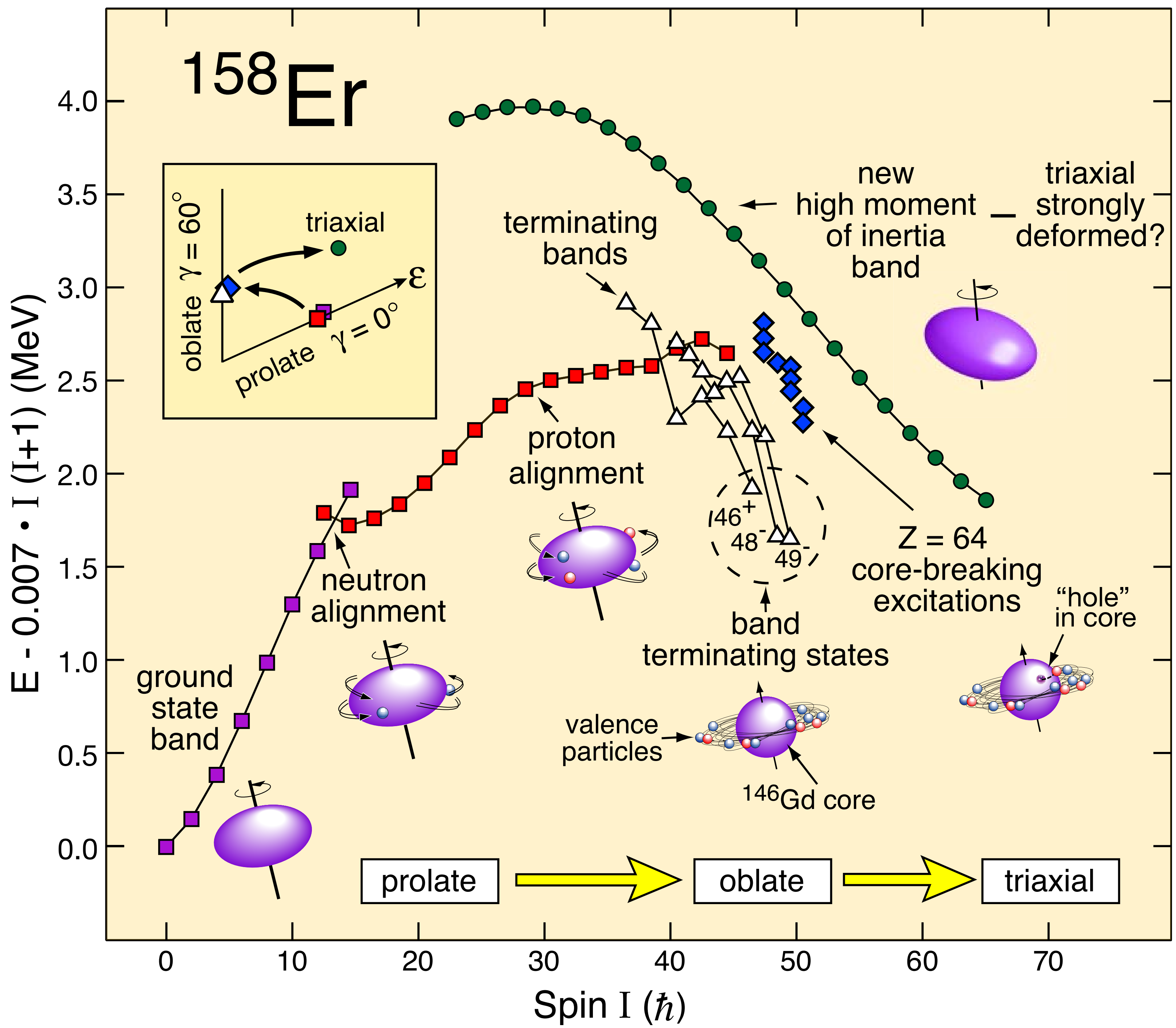


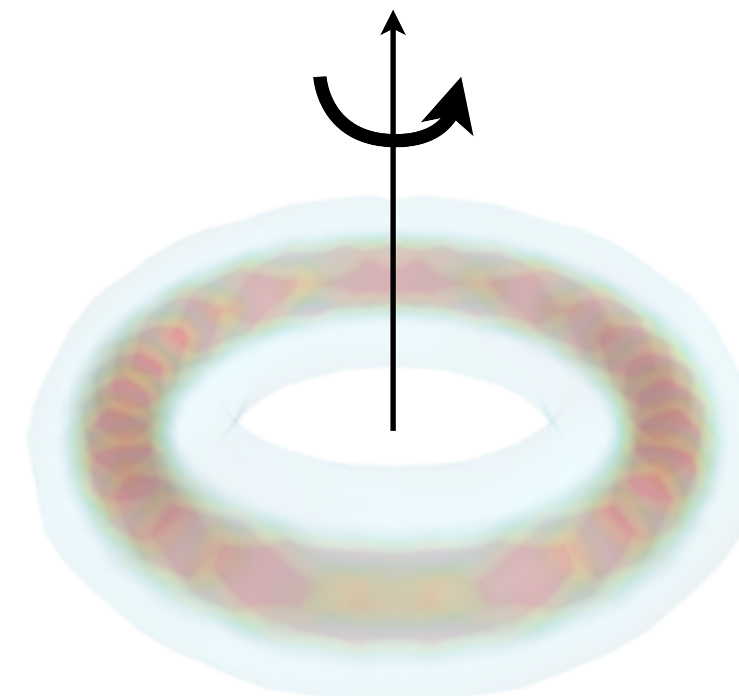
non-collective motion

By spin alignments which break the time-reversal symmetry, quantum objects can have angular momentum about the symmetry axis

Physical phenomena in high-spin states

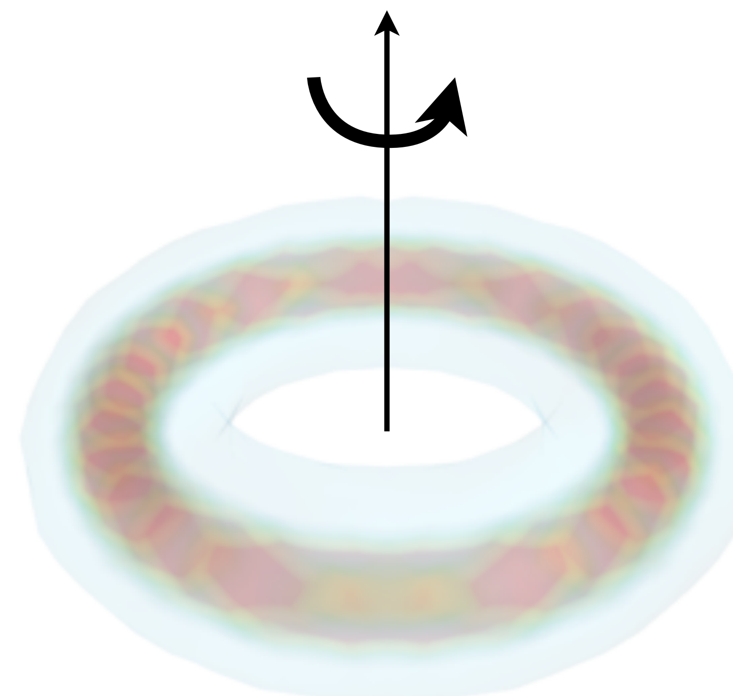
E.S. Paul *et al.*, Phys. Rev. Lett. 98, 012501 (2007)





Torus isomer is an extreme limit of oblate deformations

Objective



- A drastic example:
  If many nucleons break
  the time-reversal symmetry
  rotating about the symmetry axis
  → torus configuration
- Search for stable torus isomers in high-spin states from ^{28}Si to ^{56}Ni using the cranked Hartree-Fock (HF) method
- How is their excited states?
  → Precession motion
  → Describe the precession motion using the time-dependent Hartree-Fock (TDHF) method

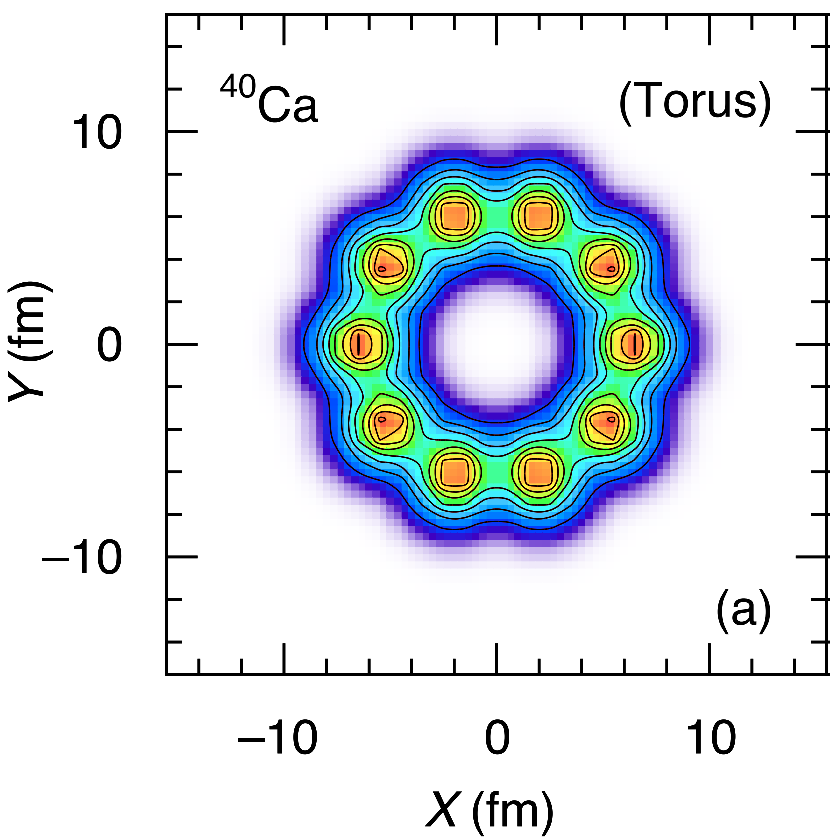
Search for torus isomer state in ^{40}Ca

Cranked 3D Hartree-Fock method

$$\delta \left\langle \hat{H} - \omega \hat{J}_z \right\rangle = 0$$

→Energy variation in the rotating frame

ω: rotating frequency of the body-fixed frame



Skyrme interactions：SLy6, SkI3, SkI4

Energy Density Functional

Spatial grid points

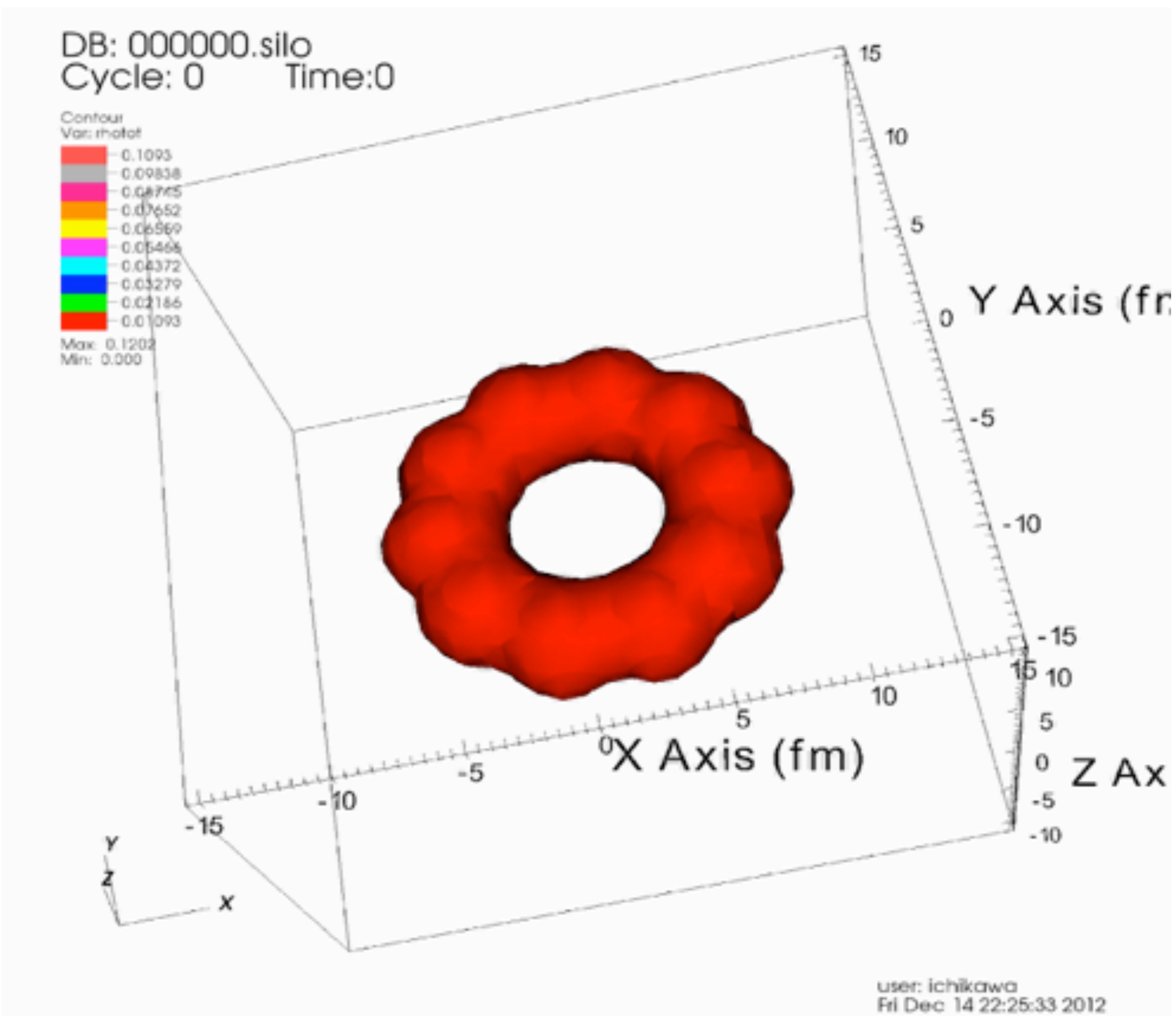
32 × 32 × 24 points

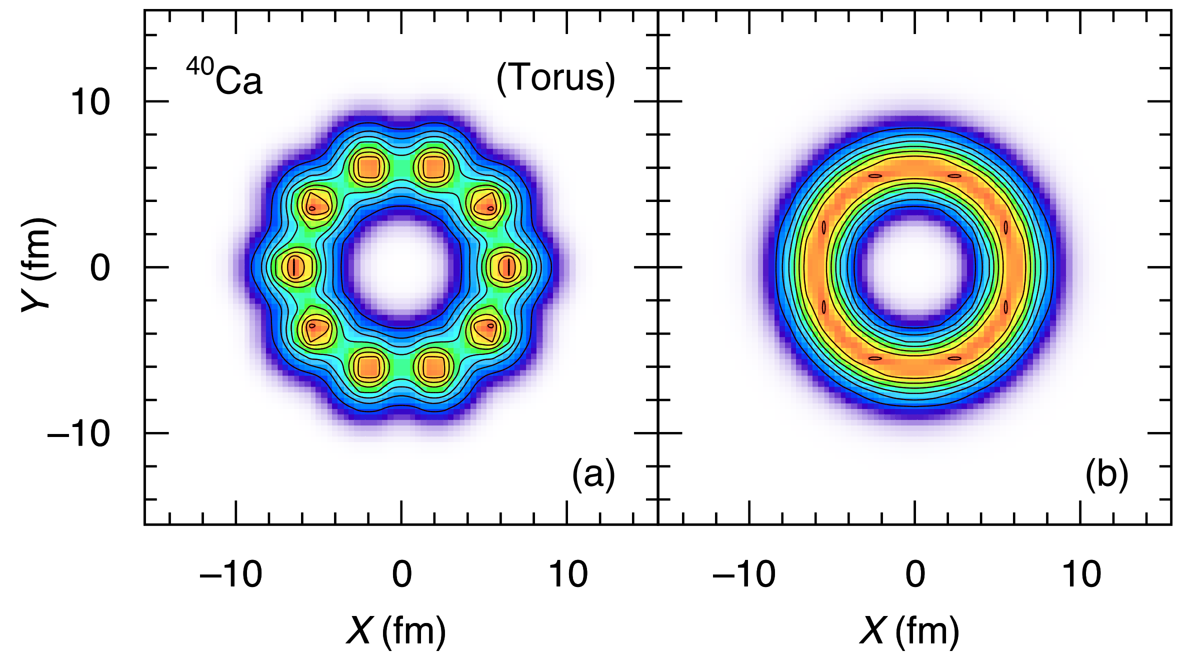
interval: 1 fm

Search for a stable state by varying various ω

Density distribution of a stable solution

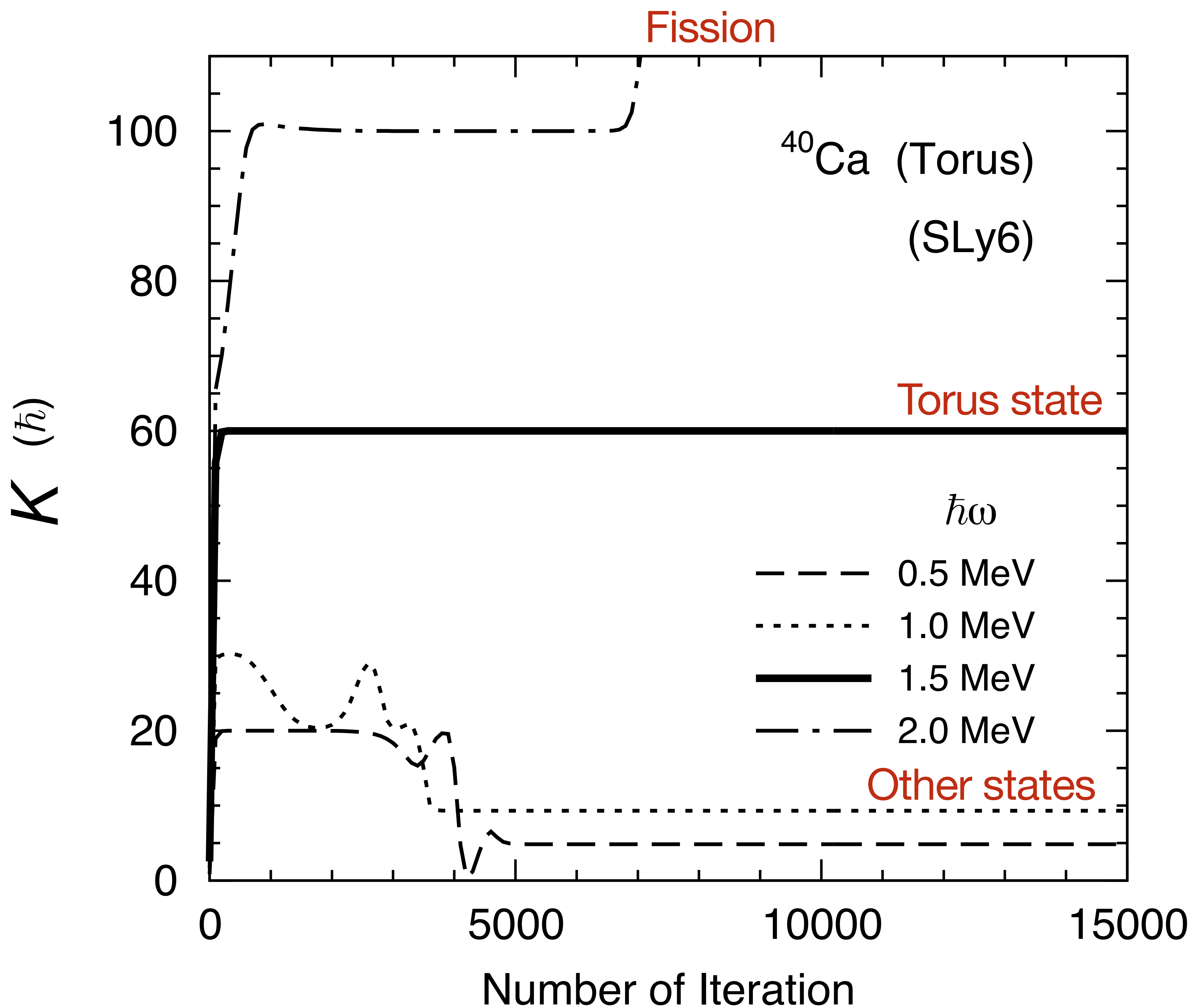
$\hbar\omega = 1.2$ MeV





$E_x = 170.45$ MeV

Convergence of K (J_z)



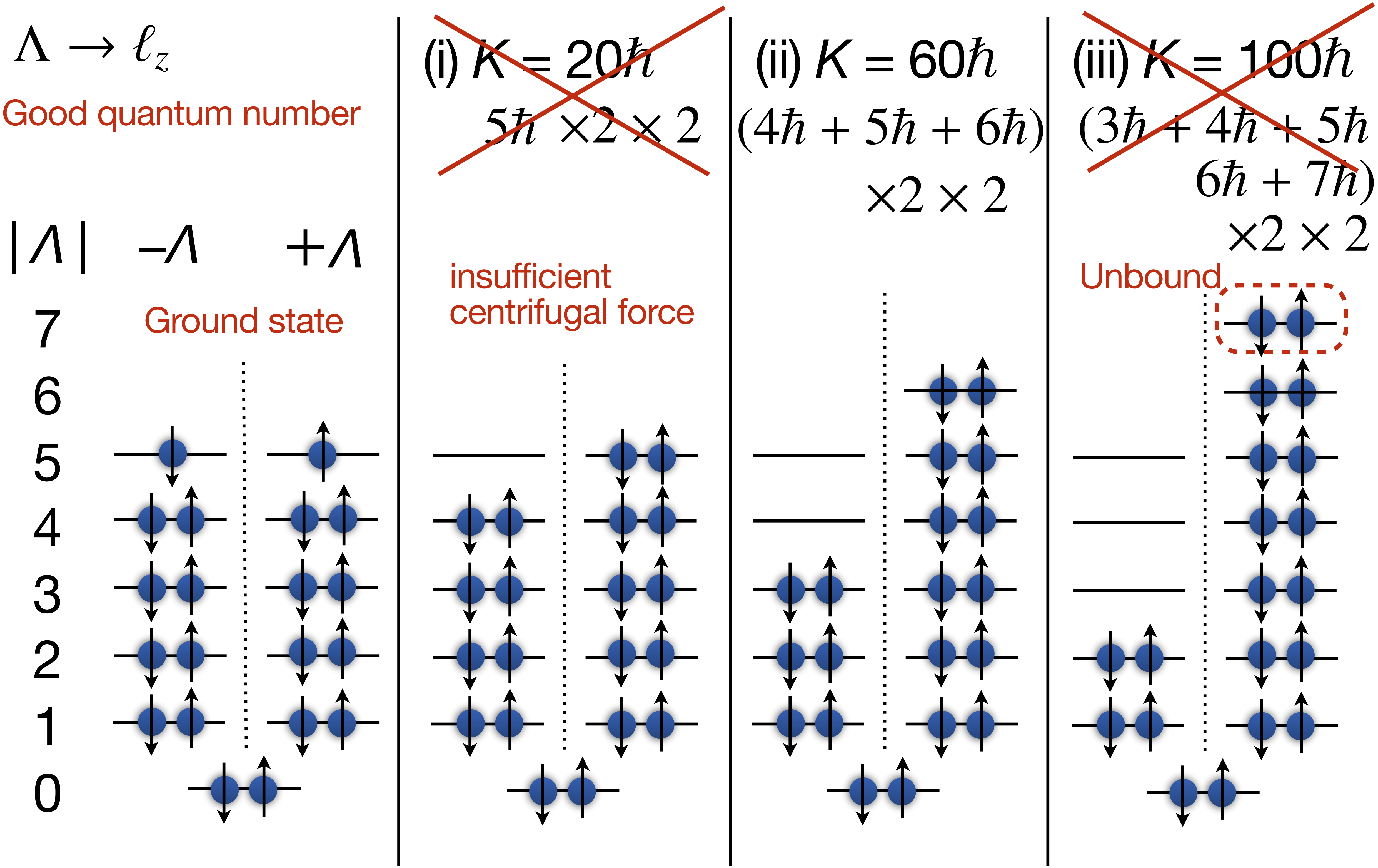
$$\delta \left\langle \hat{H} - \omega \hat{J}_z \right\rangle = 0$$

Stable solution exists from 1.2 to 1.7 MeV

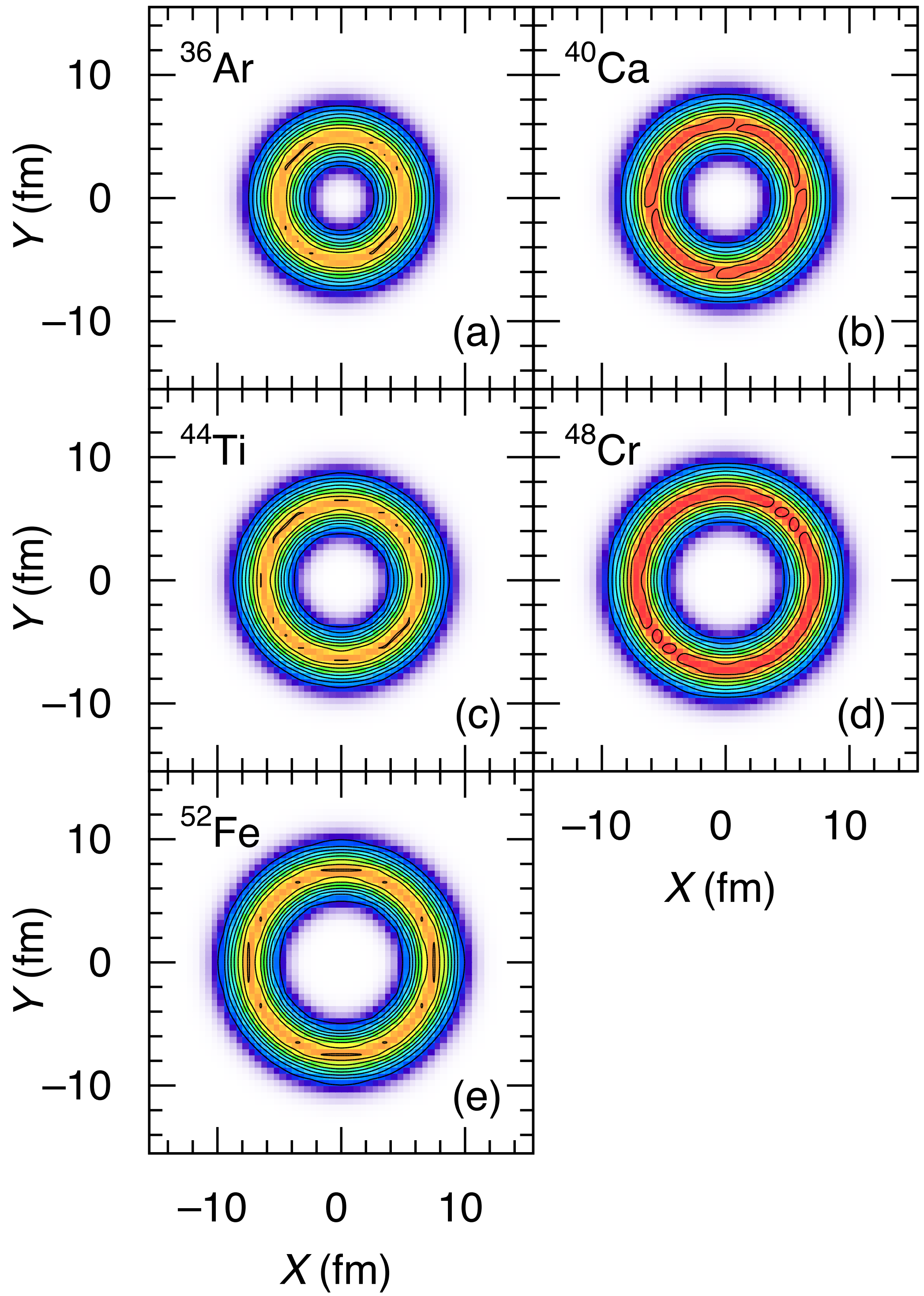
Stable solution only has $K = 60\hbar$

quasi stable state with 20 and $100\hbar$

Alignments of orbital angular momentum



Systematics of torus isomers

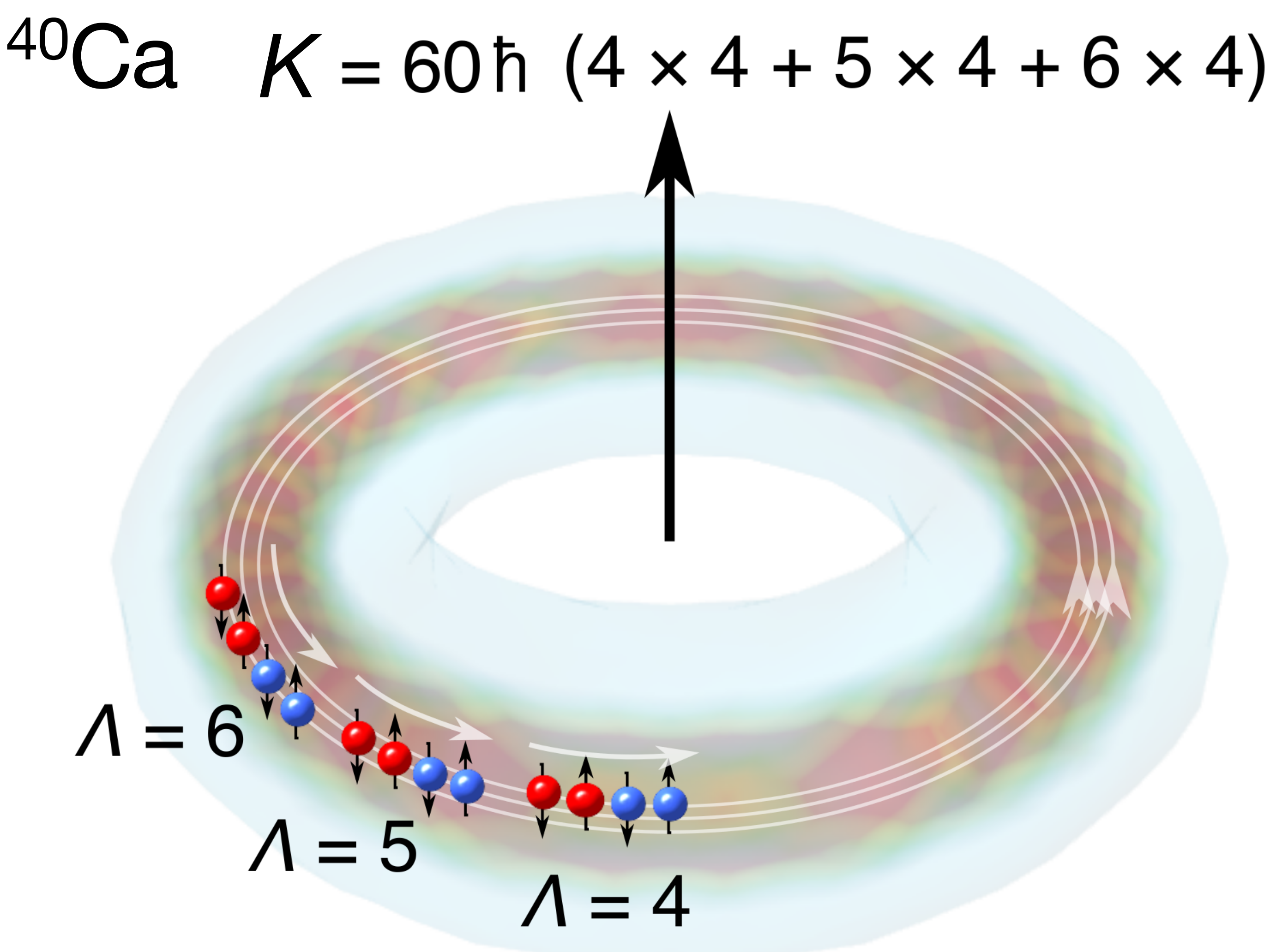


System	J_z ($\hbar$)	E_{ex} (MeV)	ρ_0 (fm^{-3})	R_0 (fm)	d (fm)
(SLy6)					
^{36}Ar	36	123.89	0.137	5.12	1.62
^{40}Ca	60	169.71	0.129	6.07	1.61
^{44}Ti	44	151.57	0.137	6.30	1.61
^{48}Cr	72	191.25	0.132	7.19	1.60
^{52}Fe	52	183.70	0.138	7.47	1.60

Density: $\rho \sim 2/3\rho_0$

Width: similar to α particle

Macroscopic current of nucleons

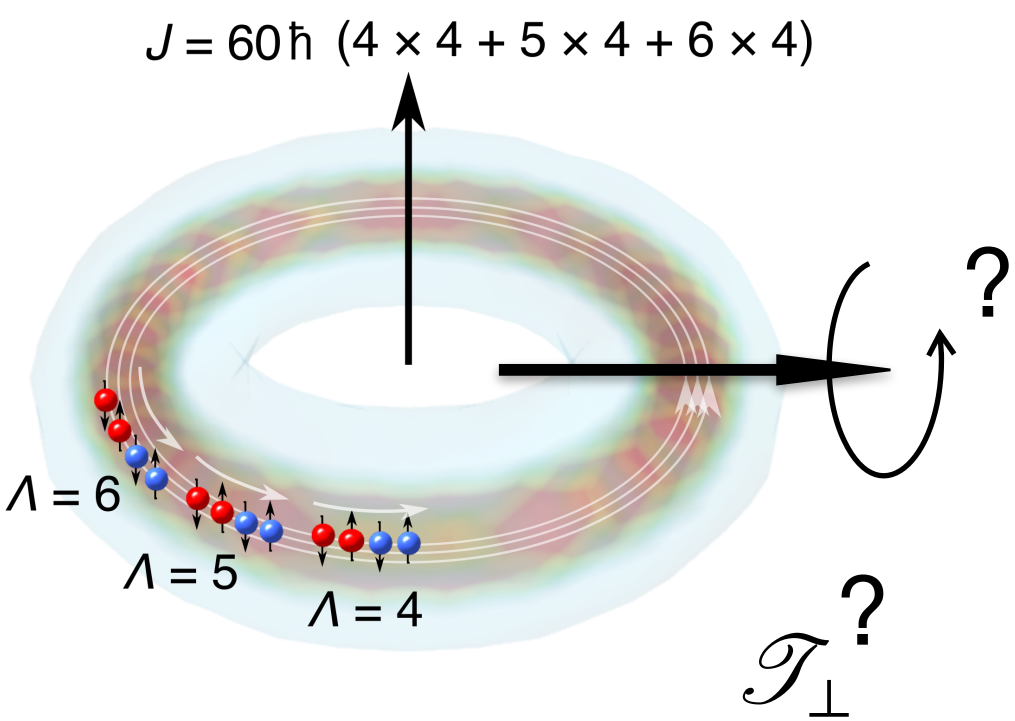


12 nucleons rotate to the same direction about the symmetry axis

Macroscopic circulating current occurs in a torus isomer

Nambu-Goldstone mode

The symmetry of the density distribution is largely broken



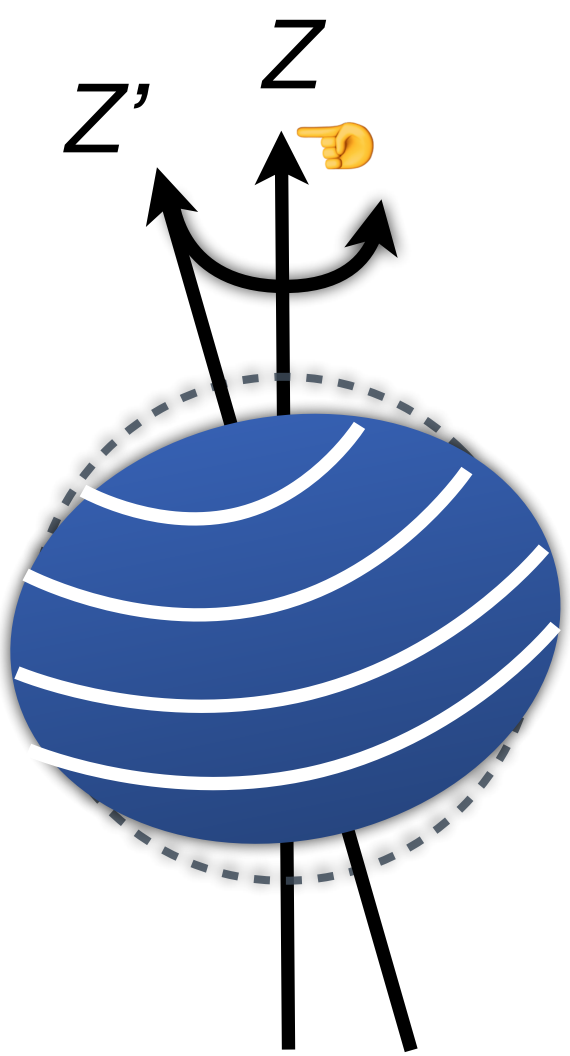
Collective motion to restore the broken symmetry should appear (NG mode)

Collective rotation about an axis perpendicular to the symmetry axis

→Precession motion

How is the moment of inertia for rotation about the axis perpendicular to the symmetry axis when macroscopic currents occur?

Precession motion



cf. a spinning top in zero gravity

Torus isomer has very large angular momentum about the symmetry axis

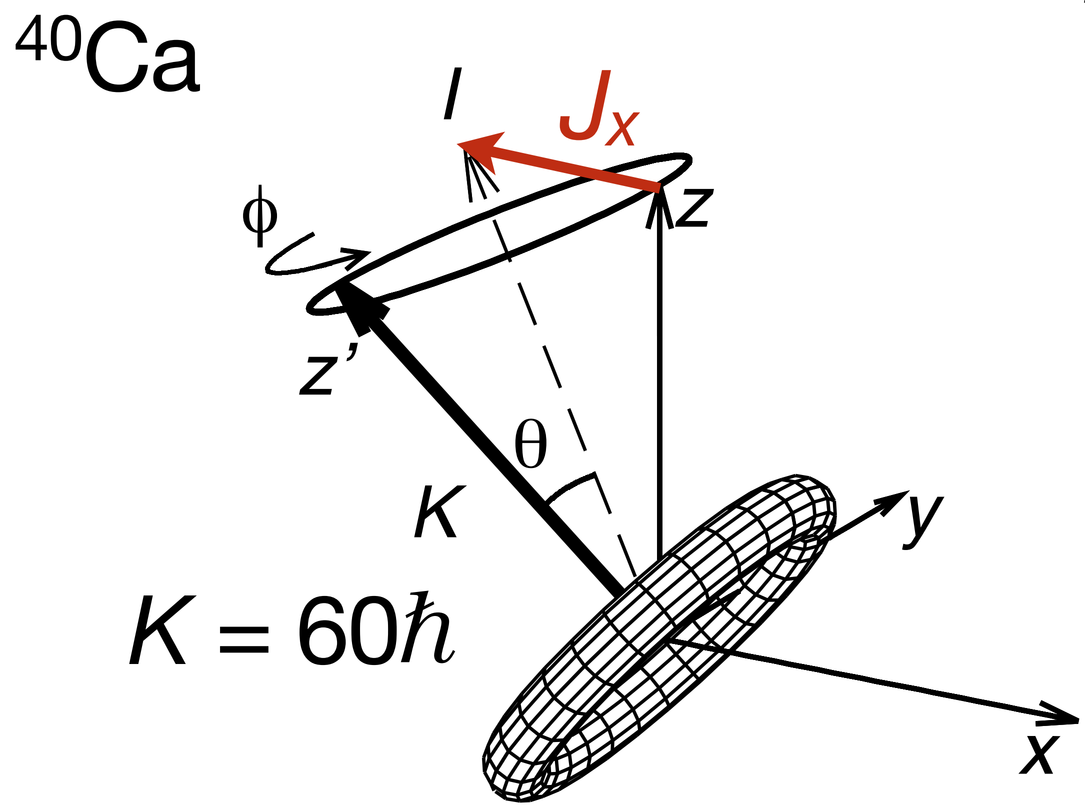
If we give an impulsive force to the symmetry axis

→ Rotation about an axis perpendicular to the symmetry axis

→ Precession motion starts

Describe the precession motion using time-dependent Hatree-Fock (TDHF) method

Schematic picture of precession motion



I: total angular momentum

$$I = K + 1 = 61\hbar$$

$$I = \sqrt{60^2 + (-11)^2} = 61\hbar$$

K $\quad$ J_x

$$\mathscr{T}_\perp = \frac{I}{\omega_{\mathrm{prec}}}$$

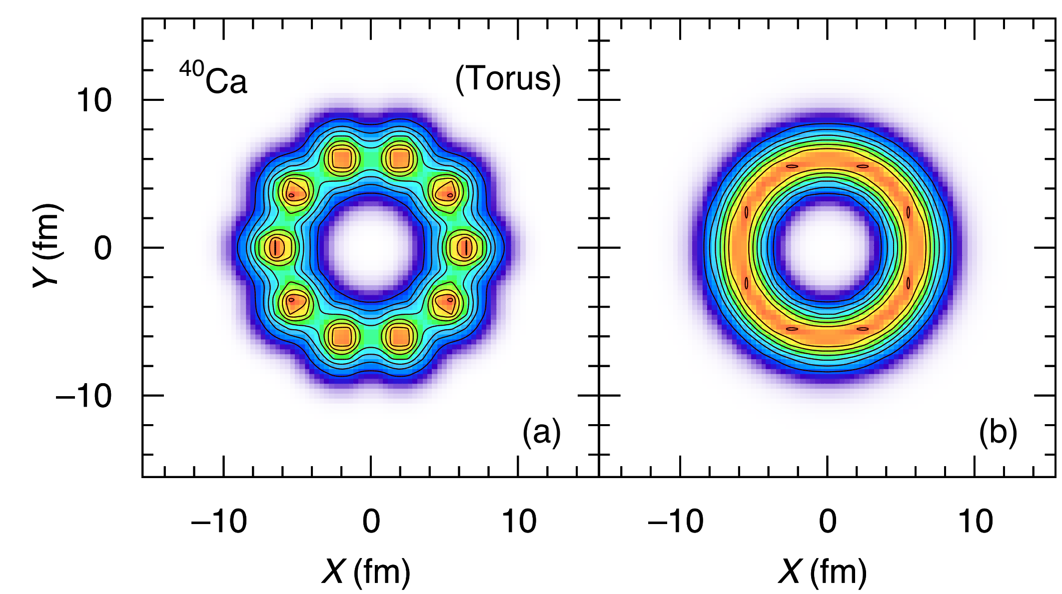
Method

- Time-Dependent Hatree-Fock (TDHF) equation

  ρ: density distribution $$i\hbar\dot{\rho} = [\hat{h}, \rho]$$

  $\hat{h}$: Hatree-Fock Hamiltonian

- Initial configuration prepare by cranked HF

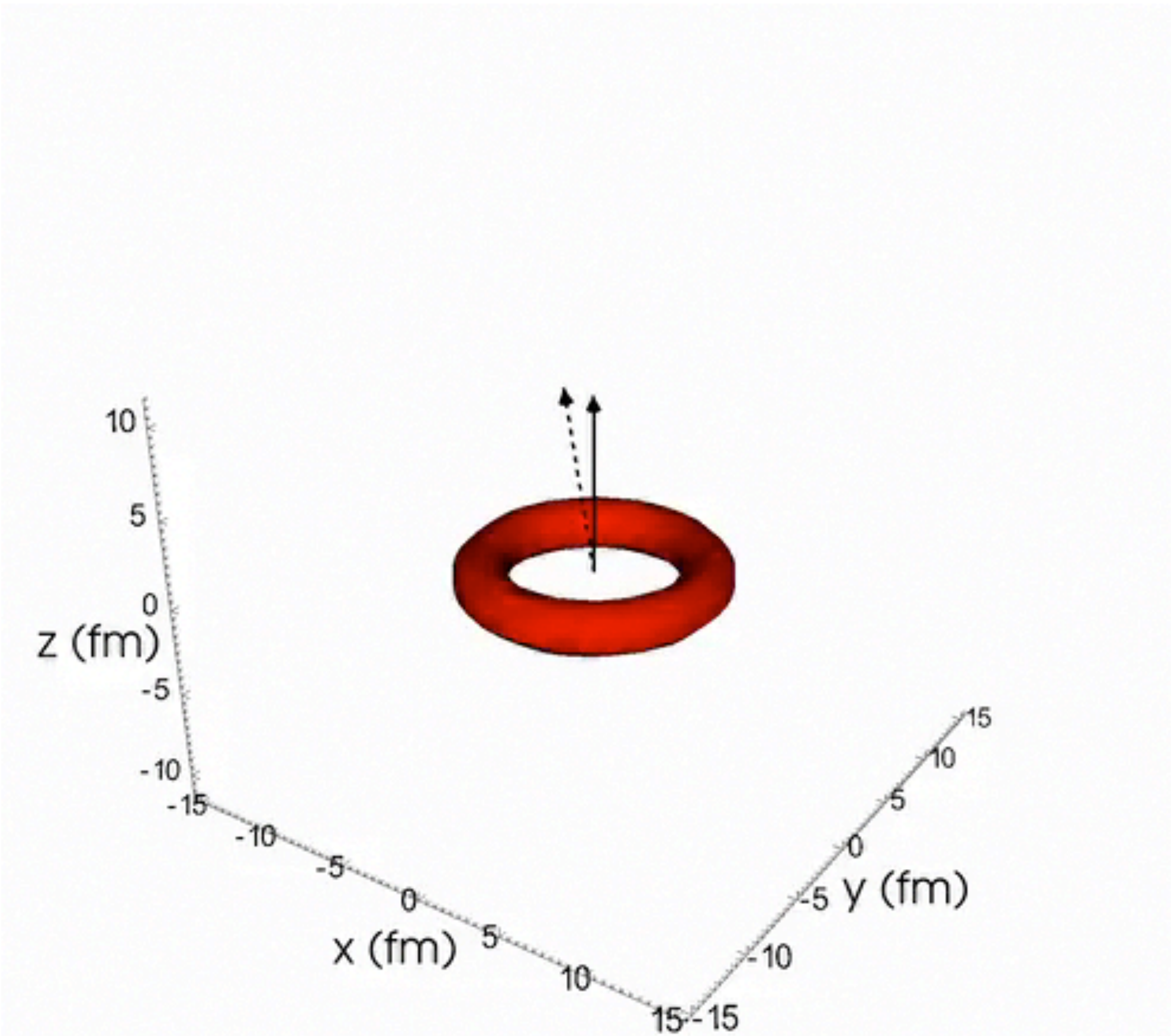


- gives an impulsive force at $t = 0$ by the external field

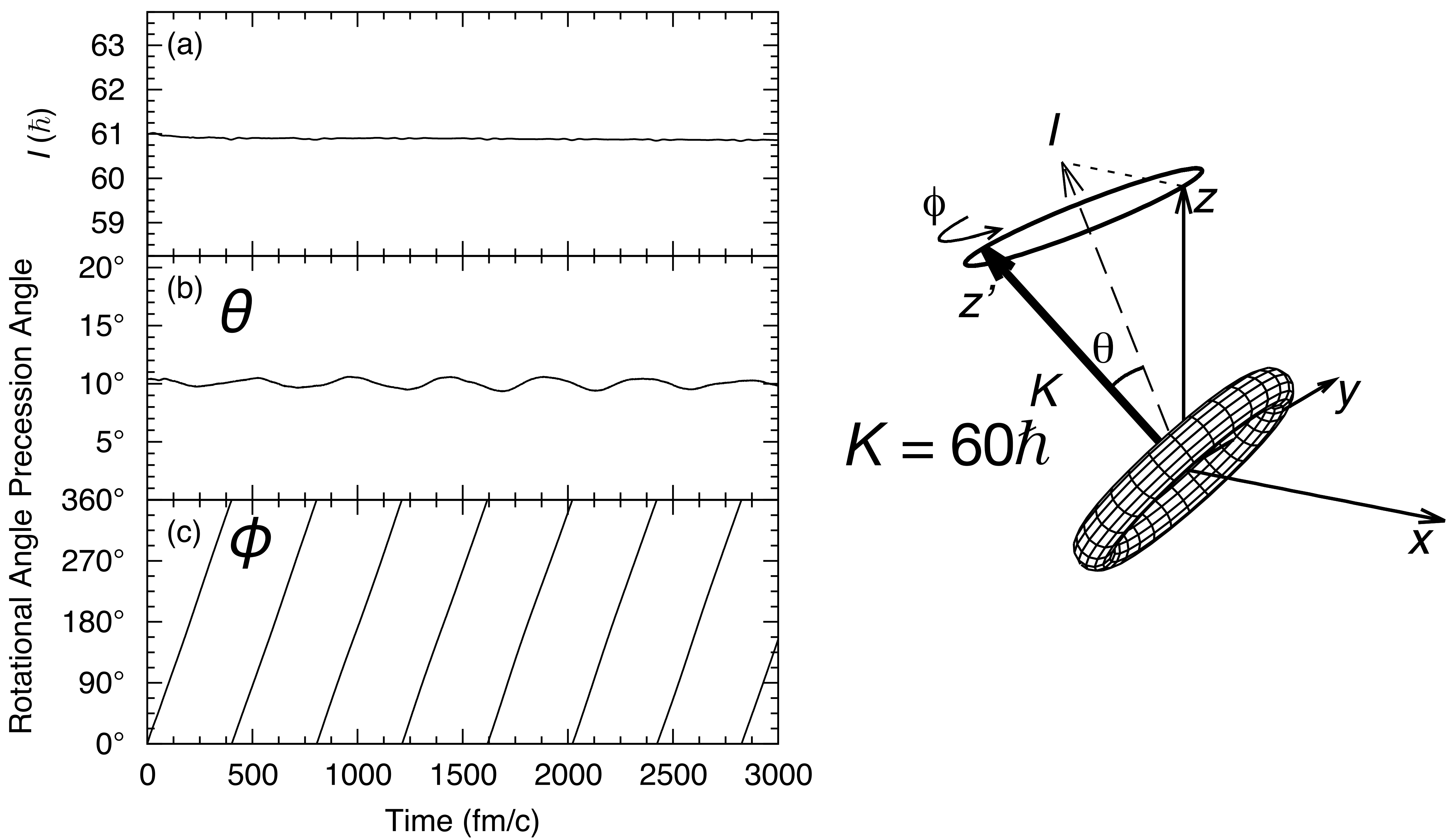
$$V_{\text{ext}}(r, \varphi, z) = V_0 z \cos\varphi \cdot e^{-(r-R_0)^2/\sigma^2}$$

$V_0 = 0.12757$ MeV

Time evolution of density distribution



Calculated results



Moment of inertia calculated by TDHF

Period	1	2	3	4	5	6	7
T_n (fm/c)	401.4	403.5	404.6	405.4	403.5	400.9	401.5

$T_{\mathrm{prec}} = 403.0$ fm/c fluctuation is very small

$$\omega_{\mathrm{prec}} = \frac{2\pi}{T_{\mathrm{prec}}} = 3.08\ \mathrm{MeV}/\hbar$$ → Excitation energy of $\Delta I = 1$

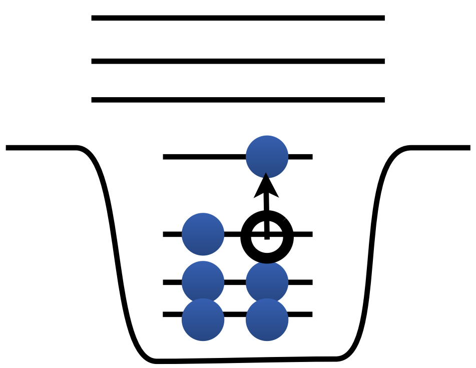
$$\mathscr{T}_{\perp}^{\mathrm{TDHF}} = \frac{I}{\omega_{\mathrm{prec}}} = 19.8\ \hbar^2/\mathrm{MeV}$$

$$\mathscr{T}_{\perp}^{\mathrm{rig}} = 21.1\ \hbar^2/\mathrm{MeV}$$

The obtained moment of inertia is almost consistent with the ridged-body one

Pure collective motion

- The random phase approximation (RPA) calculation for the precession motion (a simple model analysis)



RPA method can check whether the precession motion is the pure collective motion described by the coherent superposition of 1p-1h states or not

$$\mathscr{T}_{\perp}^{\mathrm{RPA}} = 19.6\,\hbar^2/\mathrm{MeV}$$

$$\mathscr{T}_{\perp}^{\mathrm{TDHF}} = 19.8\,\hbar^2/\mathrm{MeV}$$

$$\mathscr{T}_{\perp}^{\mathrm{rig}} = 21.1\,\hbar^2/\mathrm{MeV}$$

Surprisingly, the moment of inertia for an axis perpendicular to the symmetry axis is consistent with the classical one, although a torus isomer is pure quantum object!

Summary

- We find a stable state with the exotic torus configuration in high-spin isomer of ^{40}Ca
- To build the torus state with $K = 60\ \hbar$, the 12 nucleons for $\Lambda = 4$, 5, and 6 are aligned with the symmetry axis for both proton and neutron
- We also describe the precession motion of a torus isomer using the TDHF method
- By comparing to the RPA calculation, we found that the precession motion obtained by the TDHF calculation correspond to the excited mode generated by coherent superposition of many 1p-1h excitations

PRL 109, 232503 (2012); PRC 89, 011305(R) (2014); PRC 90, 034314 (2014)