Existence of Exotic Torus Isomer States and Their Precession Motion

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Rotation about the symmetry axis

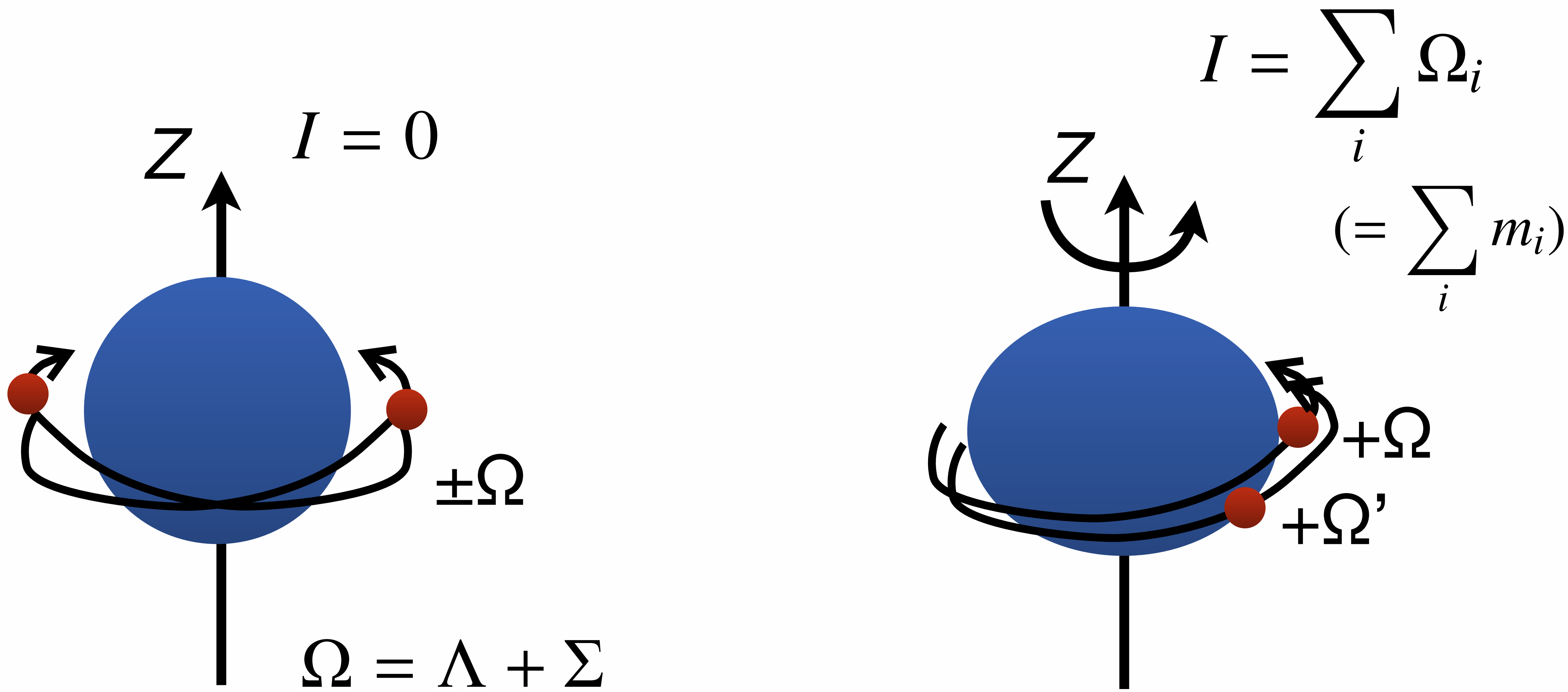
The equator part is expanded due to the centrifugal force

→Moment of inertia increases

Example: The earth

The rotation about the symmetry axis is quantum-mechanically forbidden

Spin alignments



$$\Omega = \Lambda + \Sigma$$
$$(m = \ell_z + \sigma_z)$$

non-collective motion

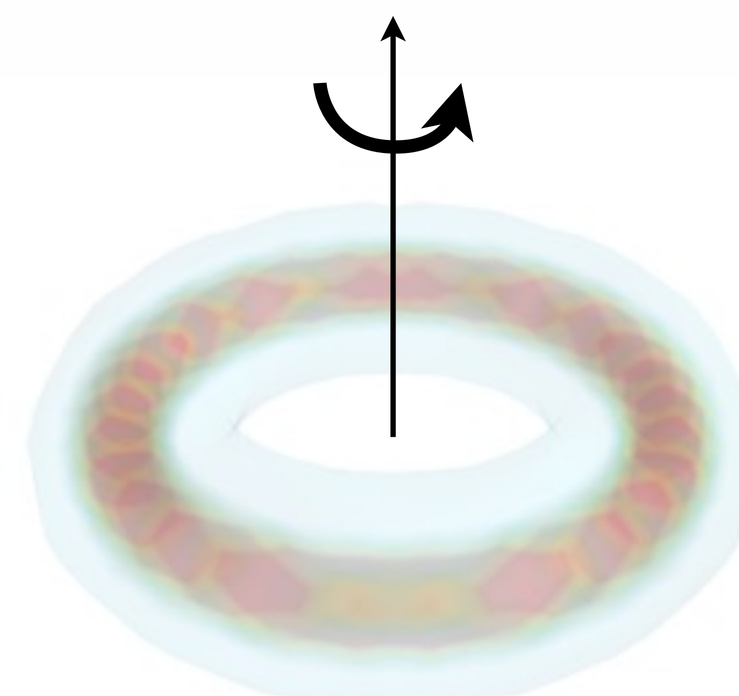
By spin alignments which break the time-reversal symmetry, quantum objects can have the angular momentum about the symmetry axis

Objective

- A drastic example:
  If many nucleons breaking the time-reversal symmetry rotates 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



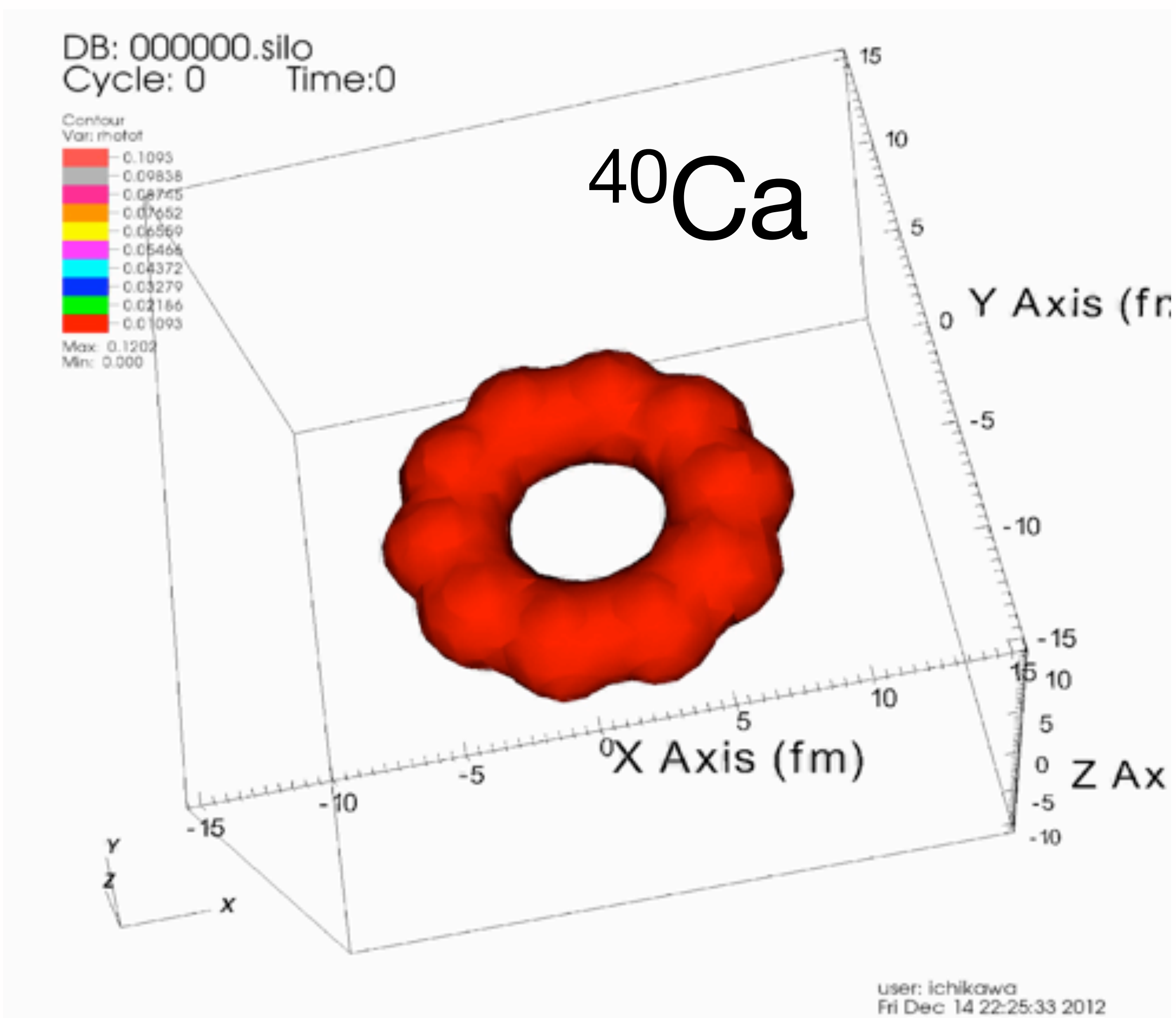
Density distribution of a stable solution

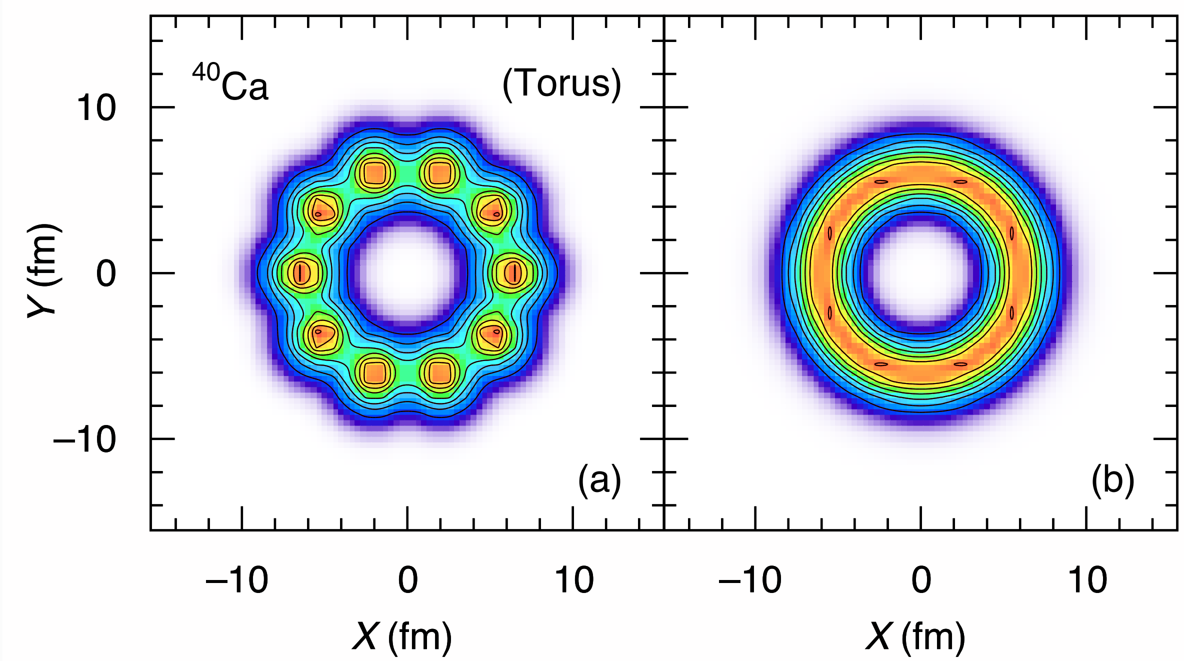
$\hbar\omega = 1.2$ MeV

Cranked 3D Hartree-Fock method
→ Code Sky3d

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

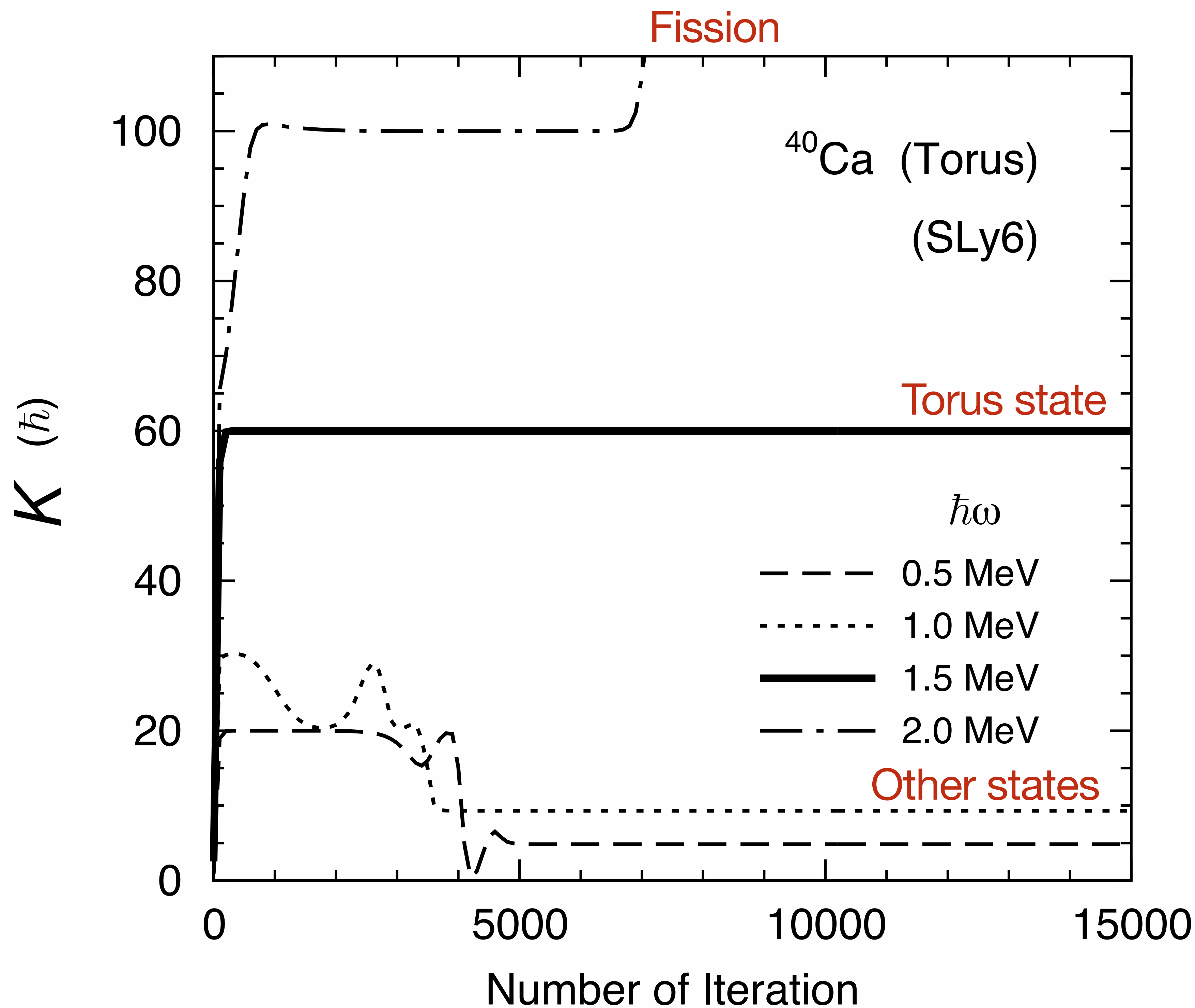
varying ω





$E_X = 170.45$ MeV

Convergence of K (J_z)

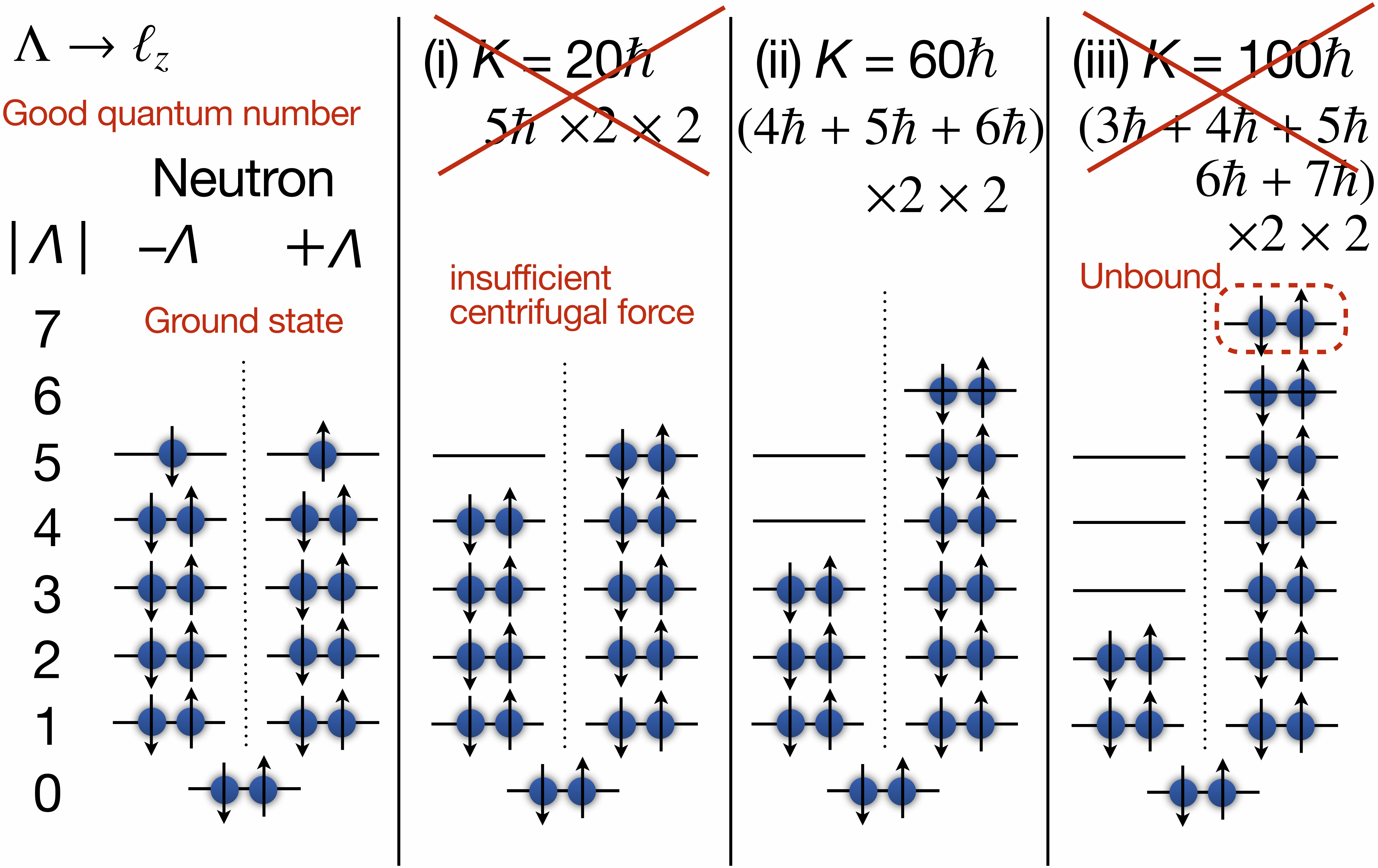


A stable solution exists from 1.2 to 1.7 MeV

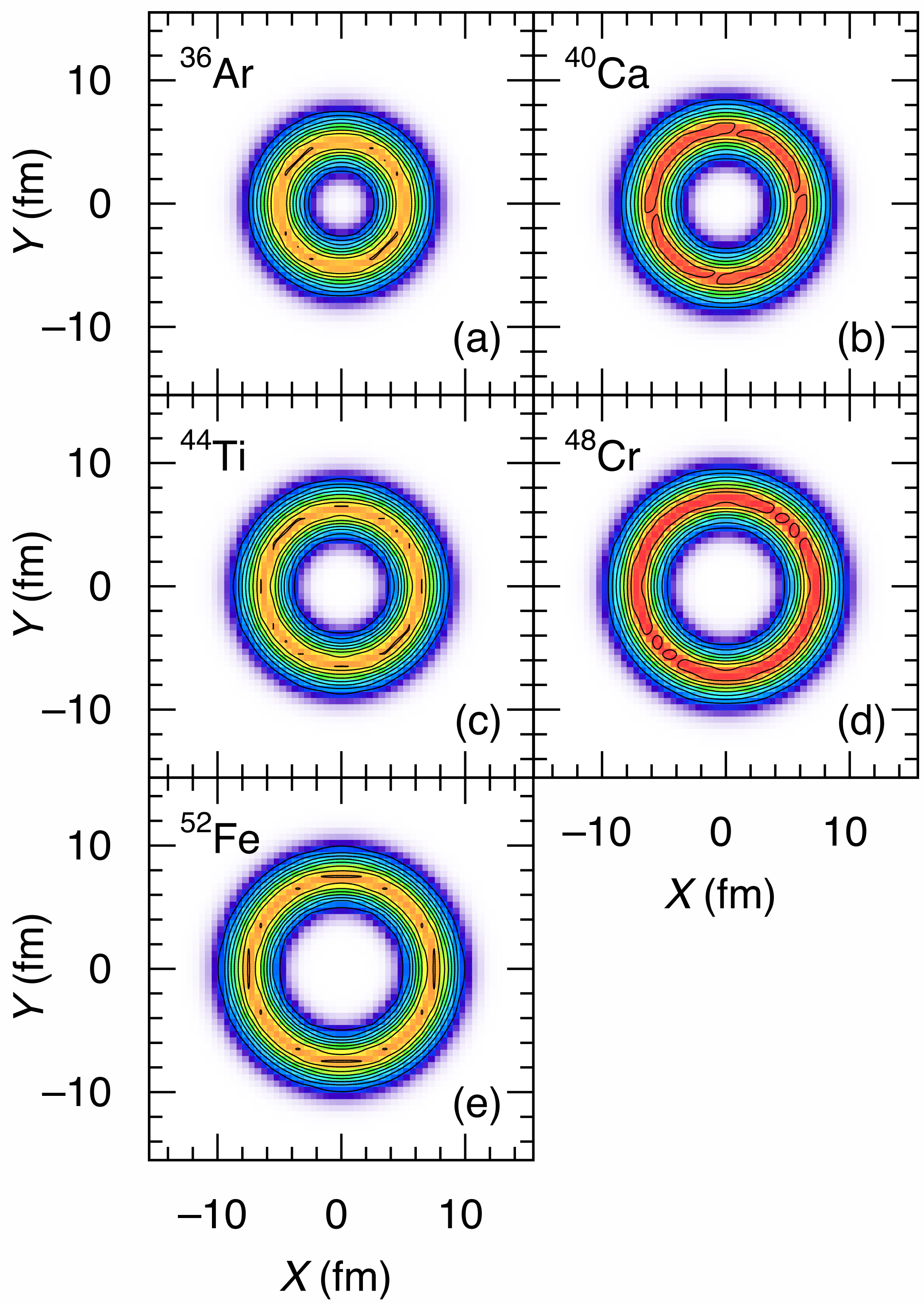
The stable solution has only $K = 60\ \hbar$

quasi stable states with 20 and 100 $\hbar$

Alignments of orbital angular momentum



Systematics of torus isomers



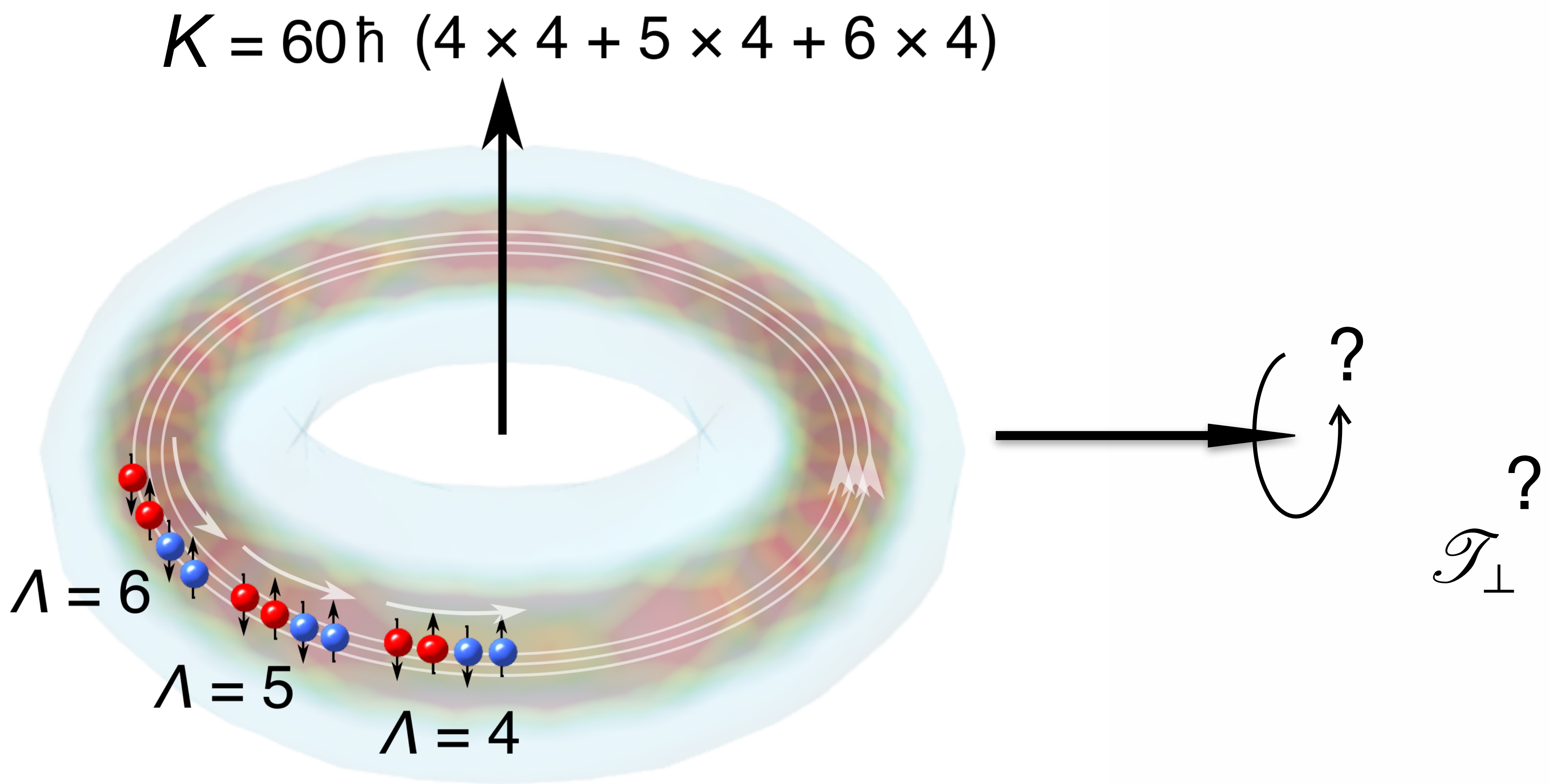
System	J_z ($\hbar$)	E_{ex} (MeV)	ρ_0 (fm^{-3})	R_0 (fm)	d (fm)	$\mathscr{T}_{\perp}$ ($\hbar^2$/MeV)	$\mathscr{T}_{\parallel}$ ($\hbar^2$/MeV)
(SLy6)							
^{36}Ar	36	123.89	0.137	5.12	1.62	14.3	26.4
^{40}Ca	60	169.71	0.129	6.07	1.61	21.1	39.6
^{44}Ti	44	151.57	0.137	6.30	1.61	24.6	46.5
^{48}Cr	72	191.25	0.132	7.19	1.60	33.8	64.7
^{52}Fe	52	183.32	0.138	7.47	1.60	39.1	75.1
(SkI3)							
^{36}Ar	36	125.15	0.146	5.01	1.58	13.7	25.3
^{40}Ca	60	173.52	0.138	5.90	1.58	19.9	37.5
^{44}Ti	44	153.02	0.146	6.17	1.58	23.6	44.6
^{48}Cr	72	193.66	0.141	7.00	1.57	32.0	61.3
^{52}Fe	52	183.70	0.147	7.31	1.57	37.5	71.9
(SkM*)							
^{36}Ar	36	124.80	0.131	5.16	1.65	14.6	26.9
^{40}Ca	60	167.84	0.122	6.17	1.64	21.8	41.0
^{44}Ti	44	152.20	0.131	6.36	1.64	25.1	47.5
^{48}Cr	72	192.40	0.125	7.30	1.63	34.9	66.7
^{52}Fe	52	187.08	0.131	7.55	1.63	40.0	76.7

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

Width: similar to α particle

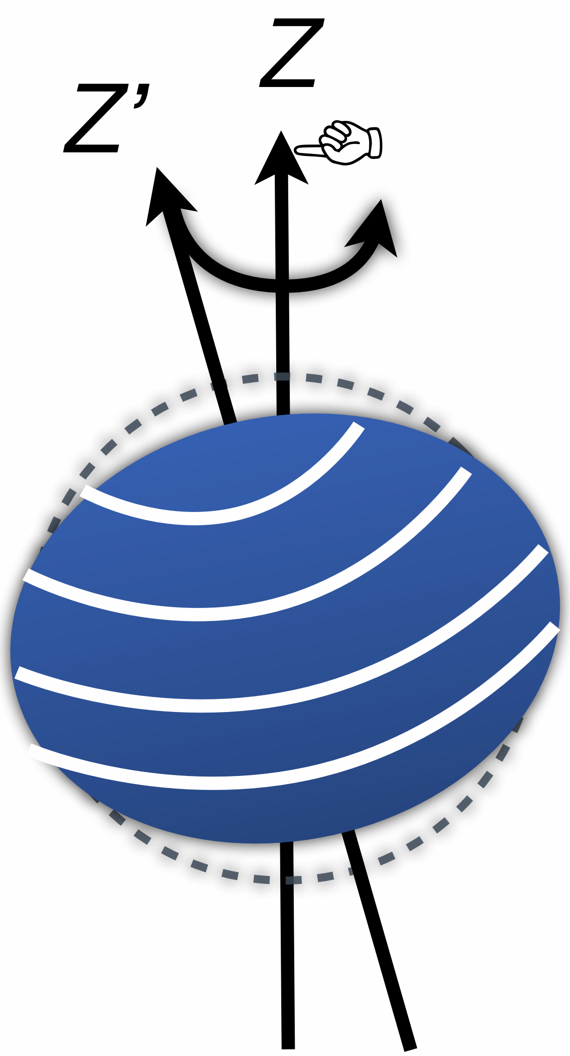
Macroscopic circulating current of nucleons

^{40}Ca



How is the moment of inertia for the rotation about an axis perpendicular to the symmetry axis when macroscopic circulating current occurs?

Precession motion



cf. a top in zero gravity

The torus isomer has a very large angular momentum about the symmetry axis

If we give an impulsive force to the symmetry axis

→ Precession motion starts

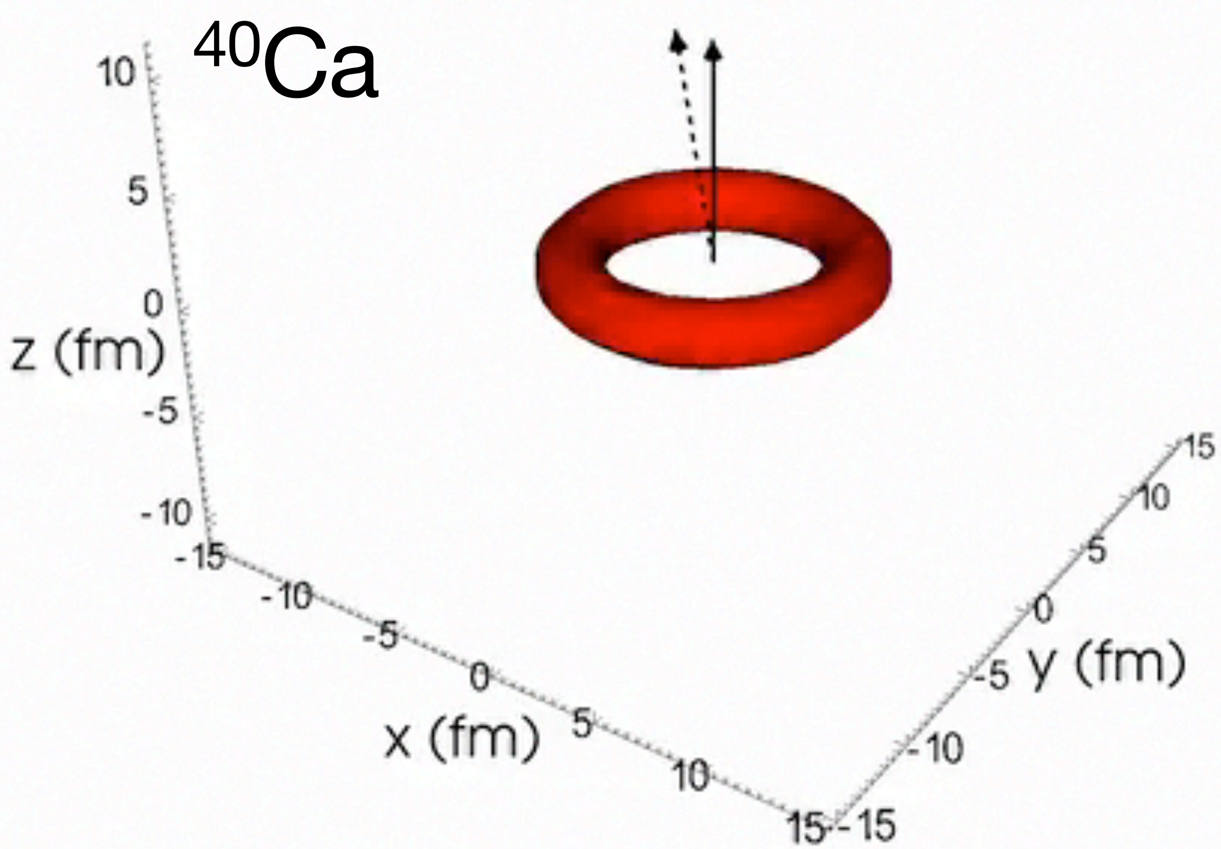
Describe the precession motion using TDHF method

Time evolution of density distribution

- TDHF equation $i\hbar\dot{\rho} = [\hat{h}, \rho]$ → Code Sky3d
- give an impulsive force at $t = 0$ by an external field

→ $I = K + 1 = 61\ \hbar$

One period: $T_{\text{prec}} = 403.0$ fm/c



$$\omega_{\text{prec}} = \frac{2\pi}{T_{\text{prec}}} = 3.08\ \text{MeV}/\hbar$$

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

→ $\mathscr{T}_{\perp}^{\text{rid}} = 21.1\ \hbar^2/\text{MeV}$

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

Summary

- We find stable isomers with the exotic torus configuration in high-spin states from ^{36}Ar to ^{52}Fe
- To build the torus isomer of ^{40}Ca with $K = 60\,\hbar$, totally 12 nucleons with $\Lambda = +4, +5$, and $+6$ are aligned with the symmetry axis in both proton and neutron
- We also describe the precession motion of torus isomers using the TDHF method and the obtained moments of inertia for the rotation about an axis perpendicular to the symmetry axis are almost the rigid-body values
- By comparing to the RPA calculation, we found that the precession motion obtained by the TDHF calculation corresponds to the excited mode generated by coherent superposition of many 1p-1h excitations

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