VORTICAL EXCITATIONS IN NUCLEI

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CCS-workshop2018, Tsukuba, Japan, 10-12.12.2018

Motivation

The toroidal dipole resonance (TDR) is interesting in many aspects:

- a remarkable example of electric intrinsic vortical motion in nuclei, which does not contribute to the continuity equation

$$\dot{\rho} + \vec{\nabla} \cdot \vec{j}_{nuc} = 0$$

Repko, P.-G. Reinhard, VON, J. Kvasil, PRC, 87, 024305 (2013).

- source of pygmy dipole resonance (PDR)
- constitutes low-energy part of ISGDR
- Hill's vortex, vortex-antivortex dipole

- Problems with TDR experiment: there are only indirect (α,α') data.

- New alternative way: recent Skyrme QRPA calculations show that in light nuclei there should exist individual dipole toroidal states (TS) with $I^{\pi}K = 1^{-}1$.

VON, A. Repko, J. Kvasil and P.-G. Reinhard, PRL 120, 182501 (2018)

Content:

- Basic information on E1 toroidal and compression resonances (theory + experiment)

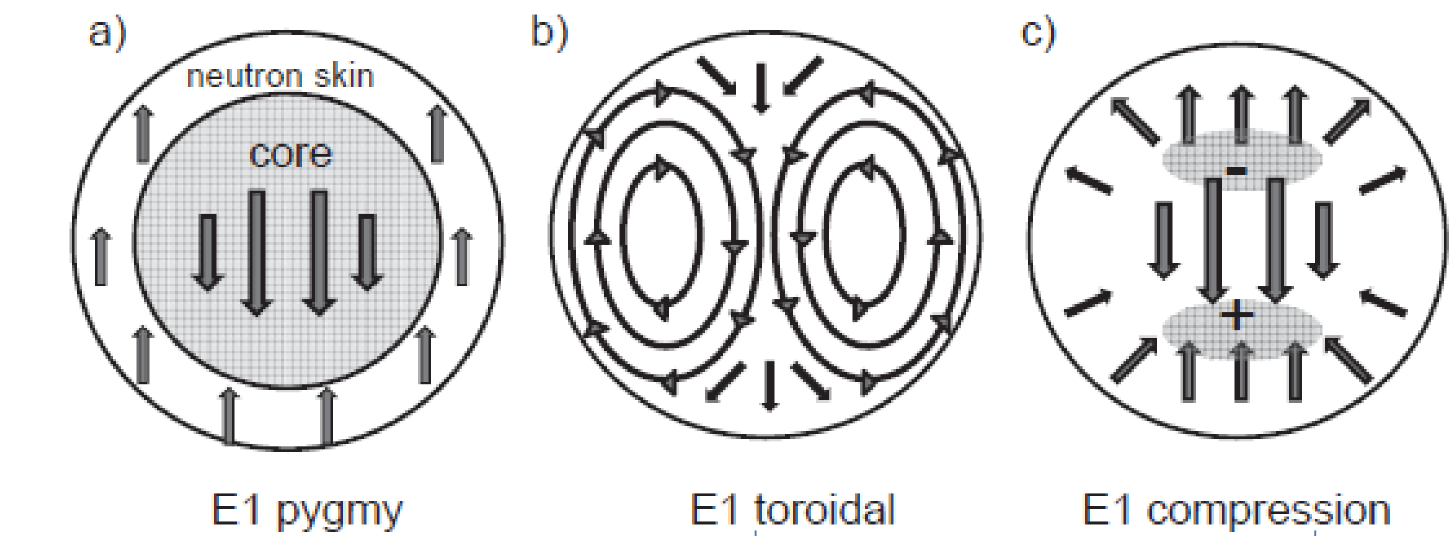
- Some points of interest for TDR:
  - TDR as a source of PDR,
  - deformation peculiarities of TDR

- Individual toroidal states in light deformed nuclei (24Mg, 20Ne)
  - Skyrme QRPA predictions
  - spectroscopy
  - relation with cluster structure

- Promising reactions to observe the toroidal flow:
  - (e,e'), …..

Exotic dipole resonances

R. Mohan et al (1971), V.M. Dubovik (1975) S.F. Semenko (1981) M.N. Harakeh (1977) S. Stringari (1982)



Alternative source of information on nuclear incompressibility

Dominate in E1(T=0) excitation channel
(due to suppression of dominant E1(T=1) motion)

irrotational	vortical	irrotational
$E = 50 \div 60\ A^{-1/3} MeV$	$E = 50 \div 70\ A^{-1/3} MeV$	$E = 132\ A^{-1/3} MeV$

- Different kinds of dipole oscillations with fixed c.m.

Reviews:
N. Paar et al, Rep. Prog. Phys. 70 691 (2007);
D. Savran et al, Prog. Part. Nucl. Phys. 70, 210 (2013)
VON, J. Kvasil, A. Repko,W. Kleinig, and P.-G. Reinhard, Phys. Atom. Nucl. 79, 842 (2016).

J. Kvasil, VON, W. Kleinig, P.-G. Reinhard, P. Vesely, PRC, 84, 034303 (2011)

Toroidal E1 operator:

$$\hat{M}_{tor}(E1\mu) = \frac{1}{10\sqrt{2}c}\int d\vec{r}\,[r^3 + \frac{5}{3}r < r^2 >_0]\,\vec{Y}_{11\mu}(\hat{\vec{r}}) \cdot [\underbrace{\vec{\nabla} \times \hat{\vec{j}}_{nuc}(\vec{r})}_{\text{vortical flow}}]$$

Compression E1 operator:

$$\hat{M}_{com}(E1\mu) = -\frac{i}{10c}\int d\vec{r}\,[r^3 - \frac{5}{3}r < r^2 >_0]Y_{1\mu}\,[\underbrace{\vec{\nabla} \cdot \hat{\vec{j}}_{nuc}(\vec{r})}_{\text{irrotational flow}}]$$

$$\dot{\rho} + \vec{\nabla} \cdot \vec{j}_{nuc} = 0$$

$$\hat{M}'_{com}(E1\mu) = \int d\vec{r}\,\hat{\rho}(\vec{r})\,[r^3 - \frac{5}{3}r < r^2 >_0]Y_{1\mu}$$

Toroidal and compression operators are coupled:

$$\hat{M}_{tor}(E1\mu) = -\frac{i}{2\sqrt{3}c}\int d\vec{r}\,\hat{\vec{j}}_{nuc}(\vec{r}) \cdot \vec{\nabla} \times (\vec{r} \times \vec{\nabla})[r^3 - \frac{5}{3}r < r^2 >_0]\,Y_{1\mu}(\hat{\vec{r}})$$

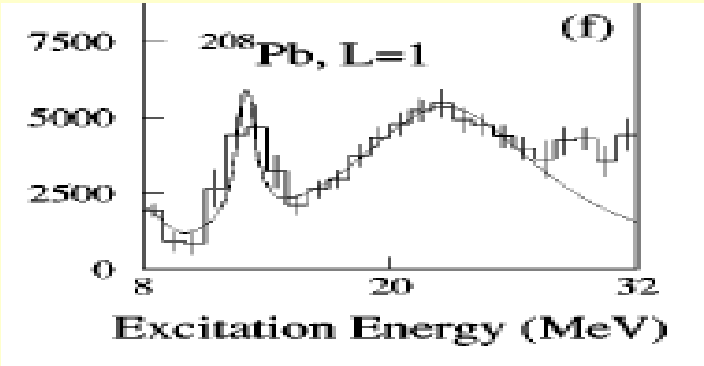
TDR and CDR constitute low- and high-energy ISGDR branches (?)

Familiar treatment → LE (toroidal) HE (compression)

Experiment: (α,α')

^{208}Pb

- D.Y. Youngblood et al, 1977
- H.P. Morsch et al, 1980
- G.S. Adams et al, 1986
- B.A. Devis et al, 1997
- H.L. Clark et al, 2001
- D.Y. Youngblood et al, 2004
- M.Uchida et al, PRC 69, 051301(R) (2004)



TDR CDR

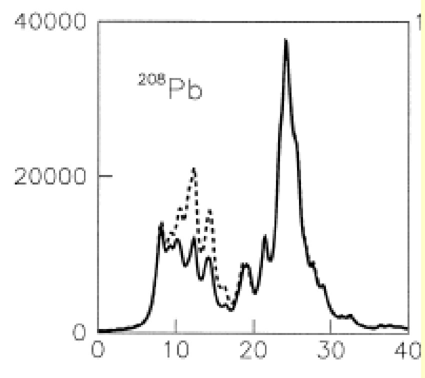
There are also exp ISGDR data in

^{56}Fe, $^{58,60}Ni$, ^{90}Zr, ^{116}Sn, ^{144}Sm, ...

Theory:

- G. Colo et al, PLB 485, 362 (2000)
- D. Vretenar et al, PRC, 65, 021301(R) (2002)
- N. Paar et al, Rep. Prog. Phys. 70 691 (2007);

A.Repko, P.-G. Reinhard, V.O.N. and J. Kvasil, PRC 87, 024305 (2013).



Perhaps Uchida observed at 10-17 MeV not TDR but CDR fraction coupled to TDR. Main TDR peak should lie lower at ~ 7-9 MeV.

The direct observation of TDR in (a,a') can be disputed in general since (a,a') is mainly determined by transition density while toroid depends on the vortical transition current.

NEED IN NEW EXPERIMENTS!

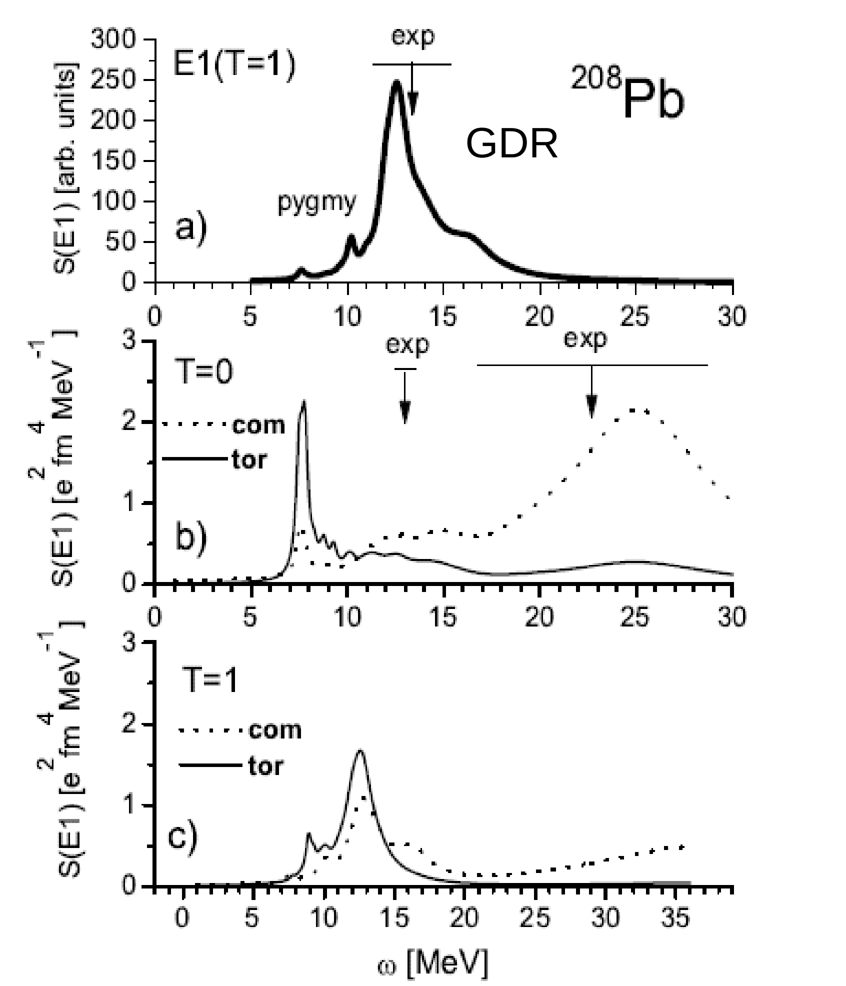
TDR as a source of pygmy resonance

Skyrme QRPA calculations

Strength functions

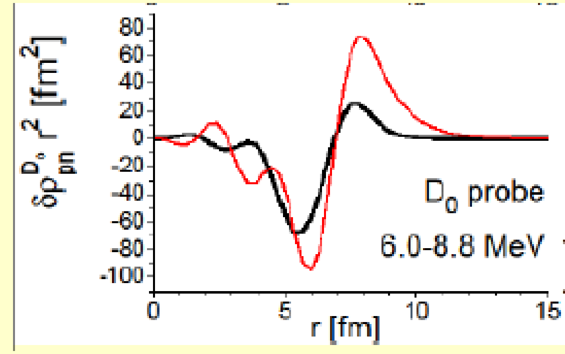
SLy6

A. Repko, P.G. Reinhard, VON, J. Kvasil, PRC, 87, 024305 (2013)



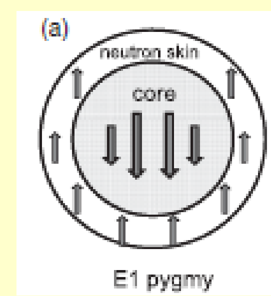
PDR region hosts TDR and CR!

Typical PDR transition density:

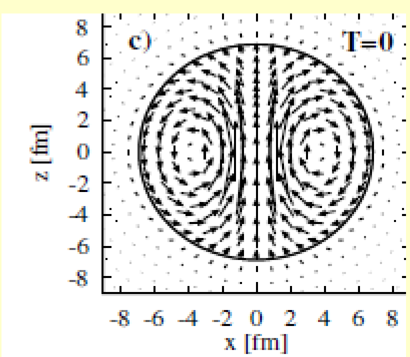


- n

- p

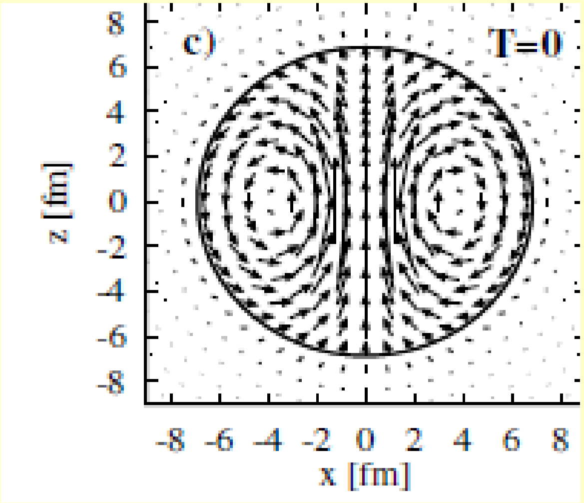


Nucleon current in the PDR region is mainly toroidal!

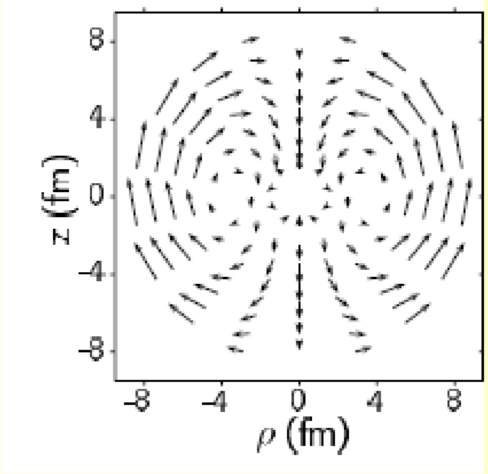


Toroidal flow in PDR energy region is obtained in various nuclei and within different models

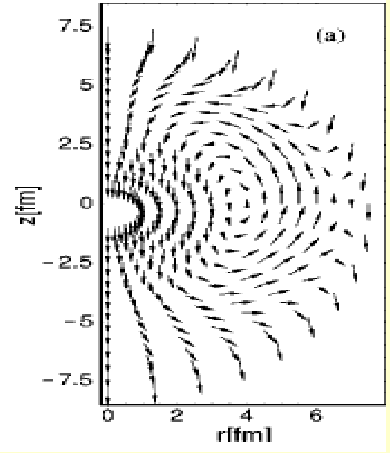
Skyrme RPA: 208Pb
Repko, P.-G. Reinhard, VON, J. Kvasil,
PRC, 87, 024305 (2013).



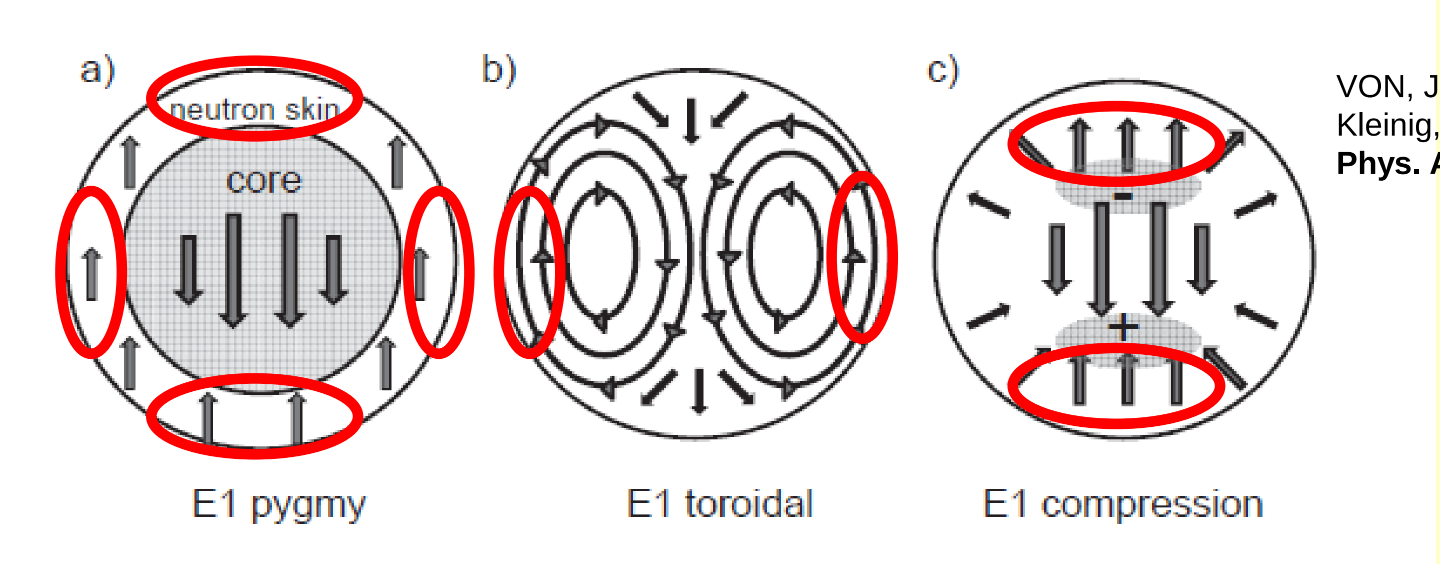
QPM: 208Pb
N.Ryezayeva et al,
PRL 89, 272502 (2002).



Relativistic RPA: 116Sn
D. Vretenar et al,
PRC 65, 021301R (2002).



Similar results in Ca, Ni,
Zr, Sn, Sm, Yb, U, ..



VON, J. Kvasil, A. Repko, W. Kleinig, P.-G. Reinhard, **Phys. Atom. Nucl.,** 79, 842 (2016).

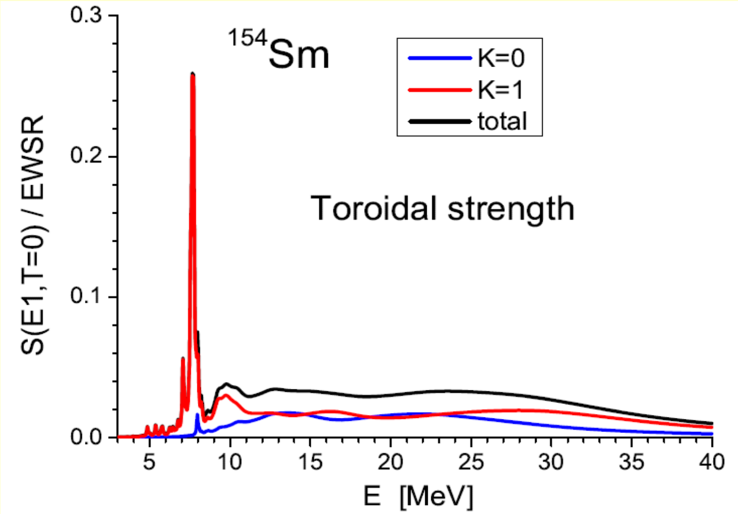
- **PDR can be viewed as a local peripheral part of TDR and CDR**

- **Such a treatment of PDR does not affect a bulk of previous theoretical and experimental results for PDR. They remain to be valid. However we obtain a better knowledge what is really happens with dipole states in the PDR region.**

Specific deformation features of TDR

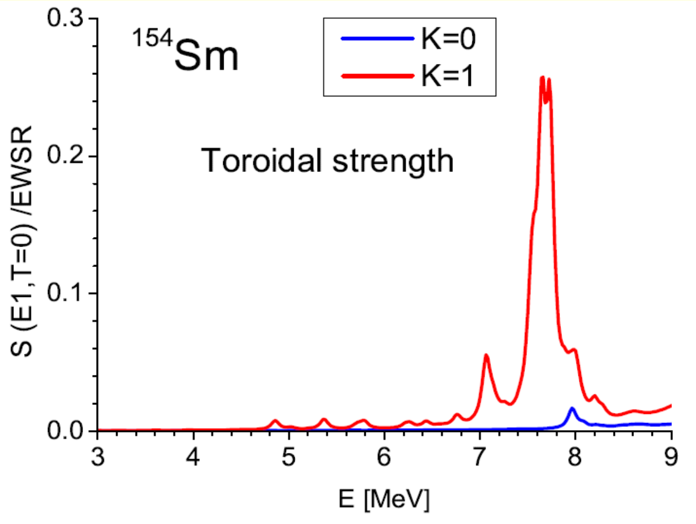
154Sm, SLy6 $\beta_2^{exp} = 0.339$

Energy-weighted strength functions

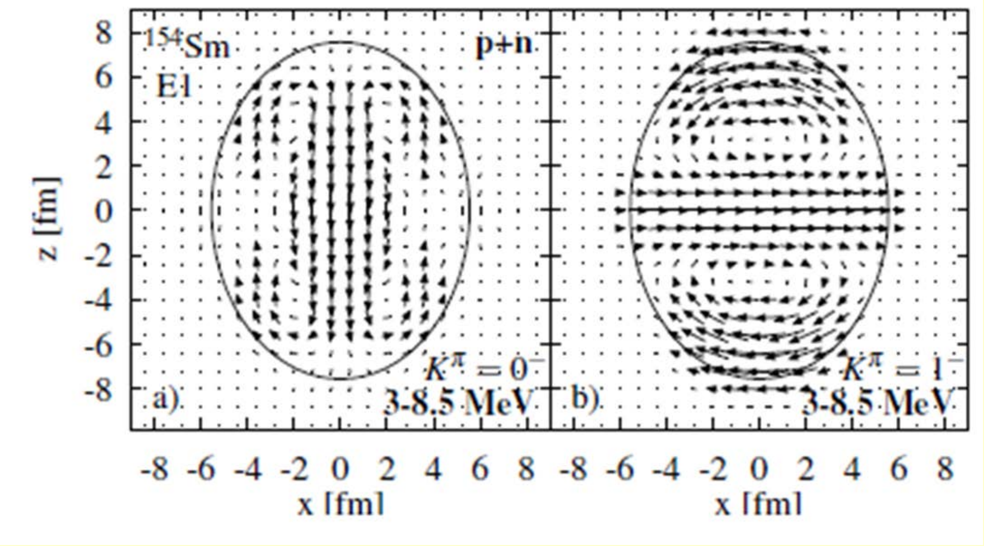


Skyrme QRPA, SLy6

A. Repko, J. Kvaail, VON,, P.-G. Reinhard, EPJA, 53, 221 (2017)



K=1 dominates !!!



Similar results for other prolate nuclei.

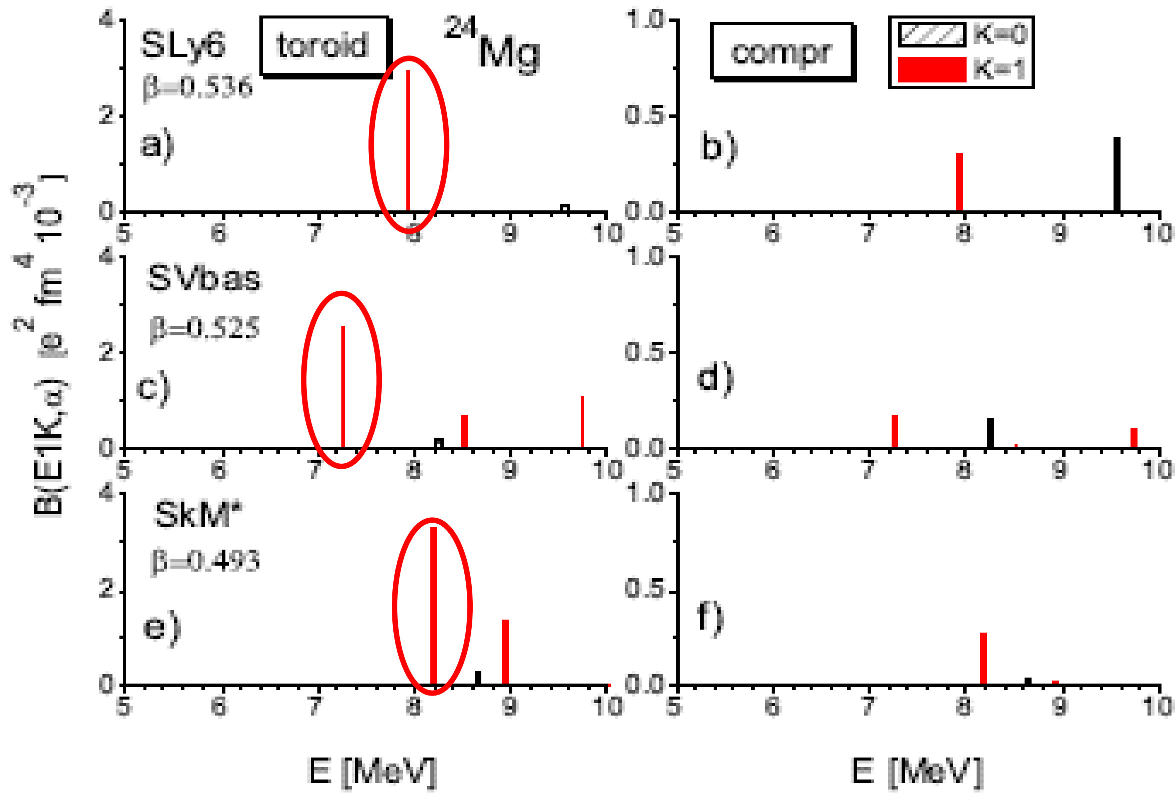
K=1 dominance can in principle be used as TDR fingerprint in future experiments.

If prolate deformation is so important, then what we will get in nuclei with a huge axial deformation, like ^{24}Mg?

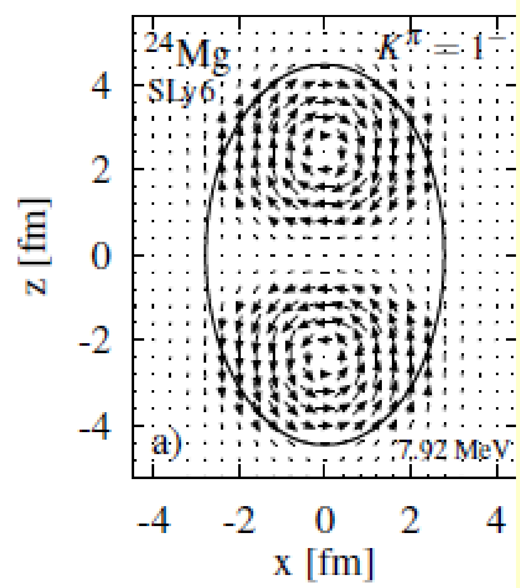
Individual toroidal states in light deformed nuclei

^{24}Mg $\beta_2^{exp} = 0.605$

VON, A. Repko, J. Kvasil, P.-G. Reinhard,
PRL 120, 182501 (2018)



QRPA results for
SLy6,
SVbas,
SkM*

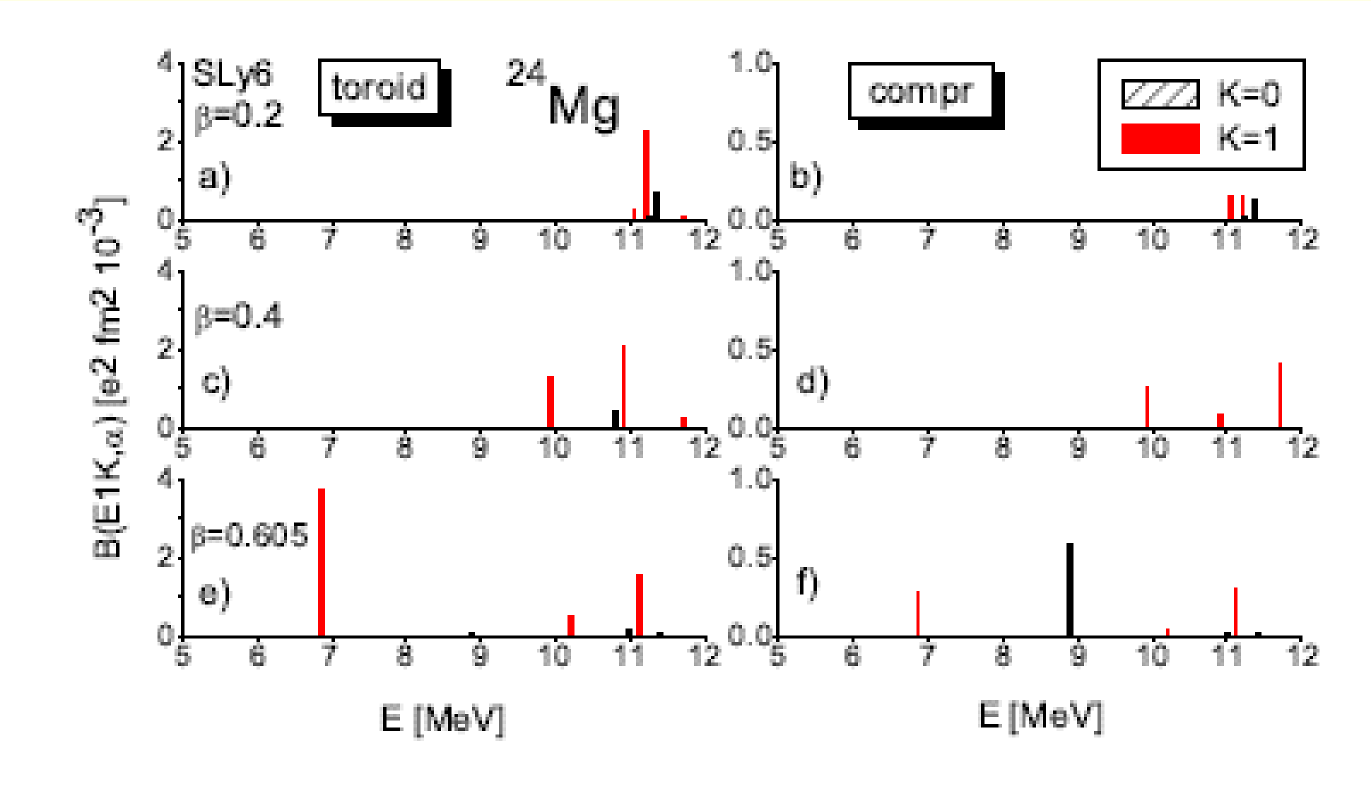


Persistence of the main result:
the **lowest** toroidal K=1 peak

The remarkable example of individual toroidal state!

Dependence on deformation

VON, A. Repko, J. Kvasil, P.-G. Reinhard, PRL 120, 182501 (2018)



TS becomes lowest due to of the large axial prolate deformation.

K=1 peak is:

- the lowest dipole state
- well separated from other states

To get individual lowest TS, two rigorous requirements should be held:

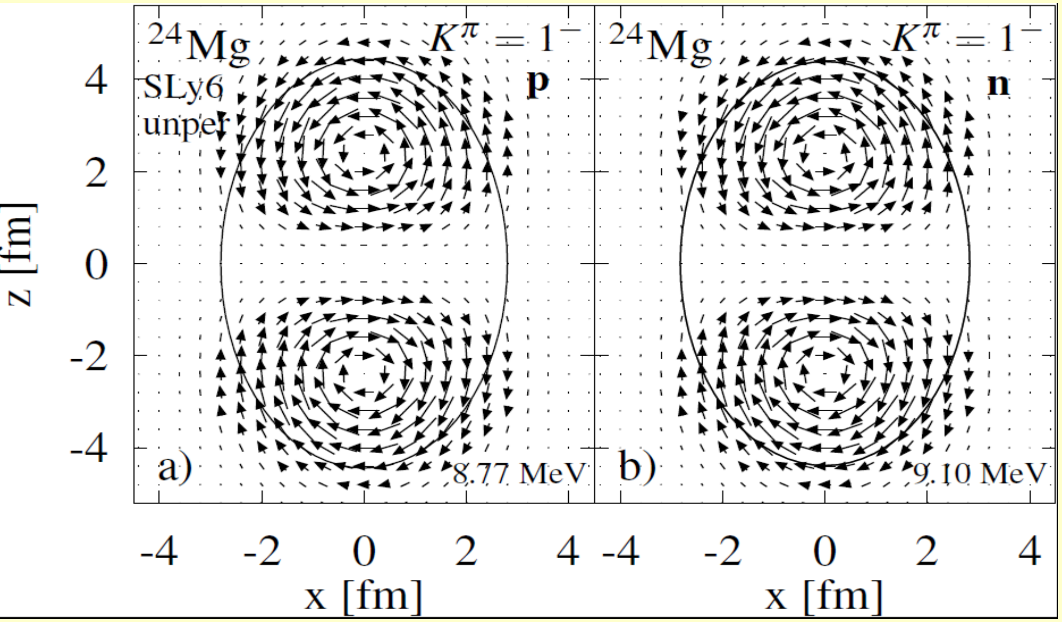
- huge prolate deformations
- sparse low-energy spectrum

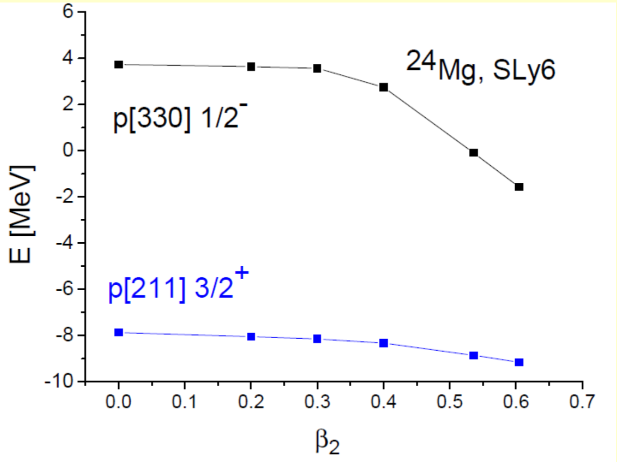
This is just realized in light deformed nuclei

Toroidal flow: collective or 2qp origin?

$pp[211]\uparrow - [330]\uparrow$ (54%)

$nn[211]\uparrow - [330]\uparrow$ (39%)





Toroid is mainly 1ph (mean field) effect!

D.G. Ravenhall and J. Wambach, NPA, 475, 468 (1987).

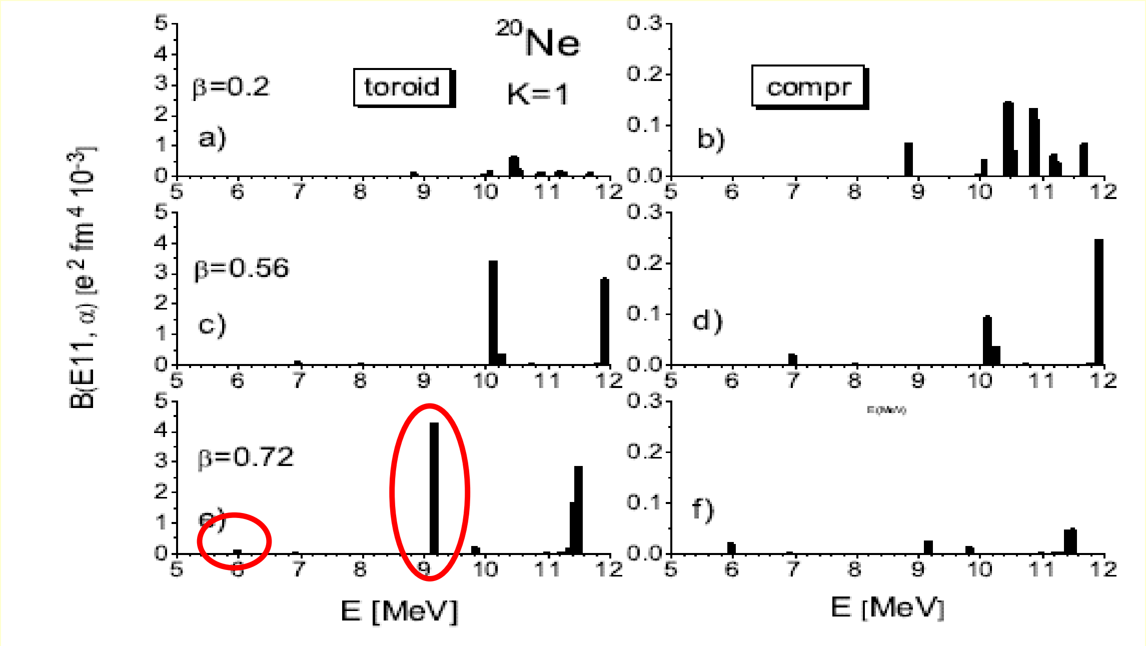
Explains the deformation effect in TS

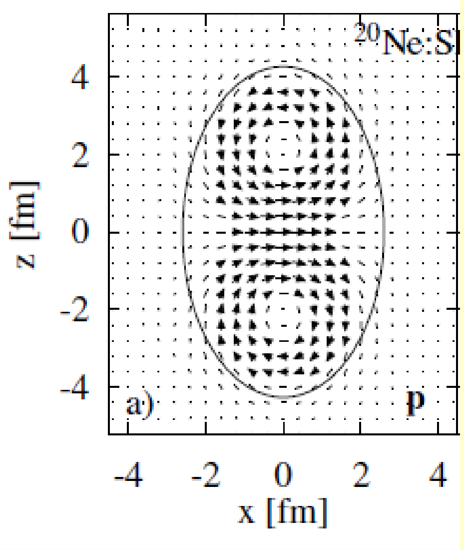
The deformation-induced energy downshift is not universal.

Perhaps ^{24}Mg is one of very few nuclei where the toroidal mode is the lowest dipole K=1 state.

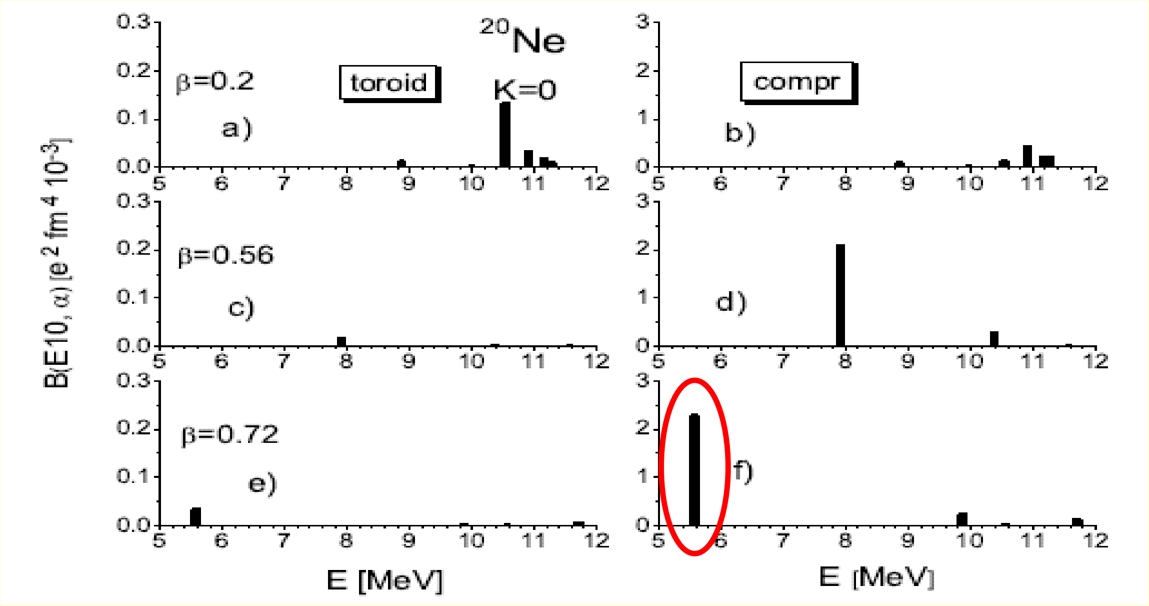
20Ne $\beta_2^{exp} = 0.72$

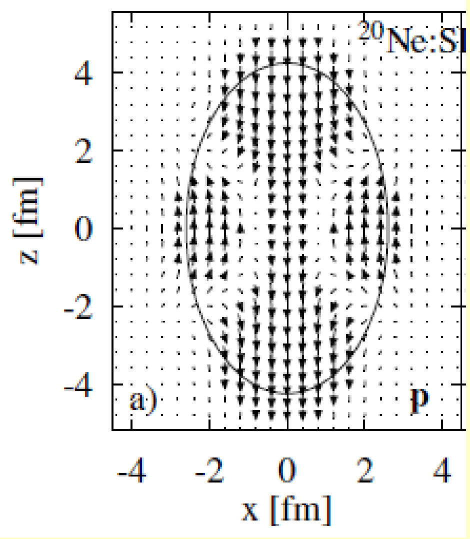
V.O. Nesterenko, J. Kvasil, A. Repko, and P.-G. Reinhard, Eur. Phys. J. Web of Conf. 194, 03005 (2018) (2018)arXiv1809.01097[nucl-th].





TM: not lowest

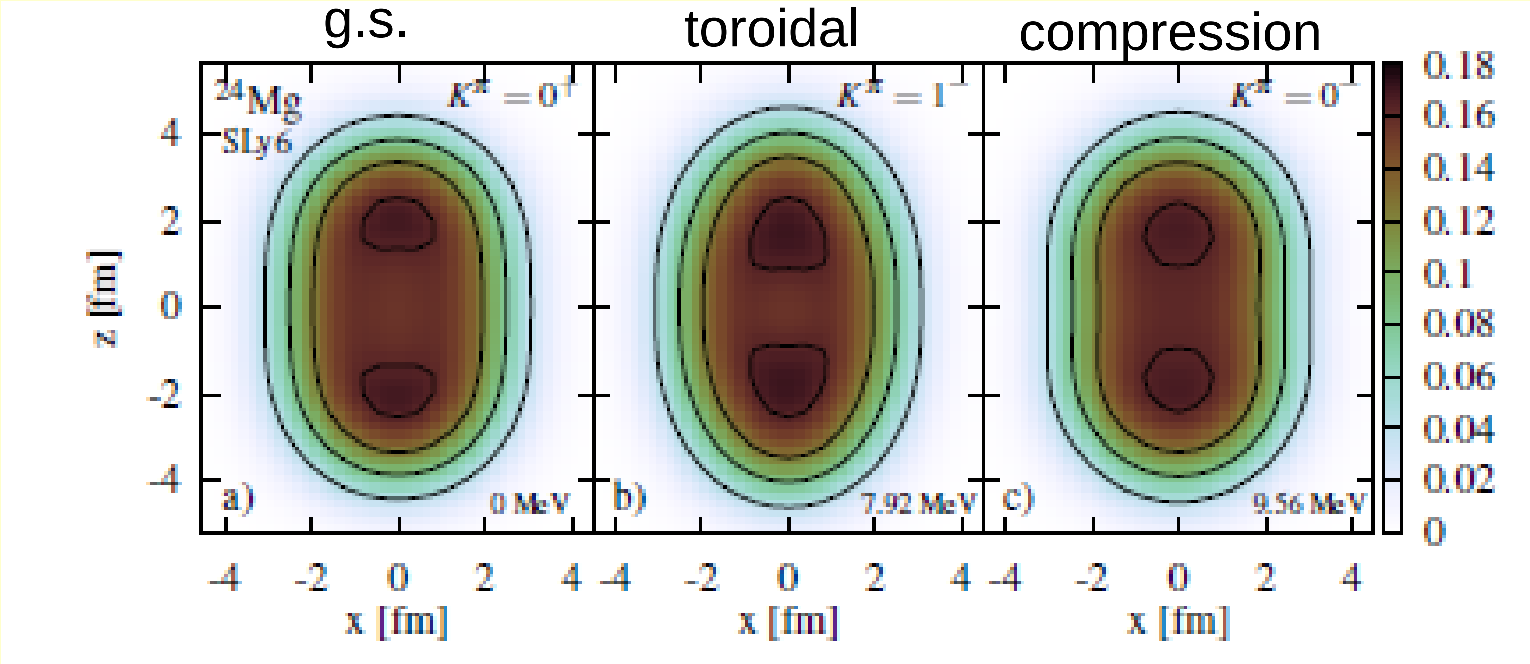




CM: lowest

VON, A. Repko, J. Kvasil, P.-G. Reinhard, PRL 120, 182501 (2018)

Relation to cluster structure of 24Mg



Densities for the ground, toroidal and compression states

- Excitation energies near α particle threshold S_α=9.3 MeV
- Cluster structure in all three states.
- Conversion of Hill's vortex ring into vortex-antivortex dipole.
- Toroidal flow looks as rotations of two clusters in the opposite directions. Some signatures?

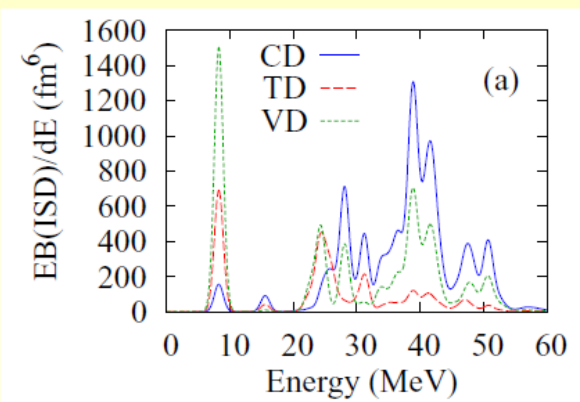
PHYSICAL REVIEW C 95, 064319 (2017)

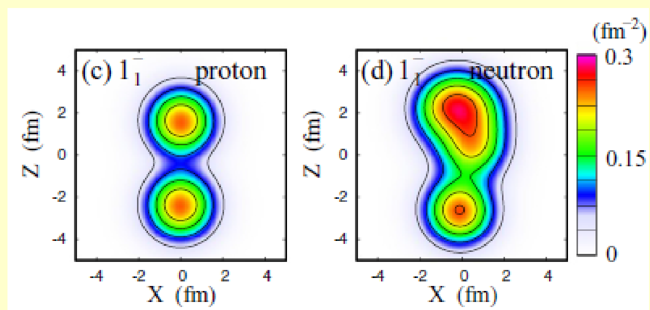
Toroidal, compressive, and $E1$ properties of low-energy dipole modes in ^{10}Be

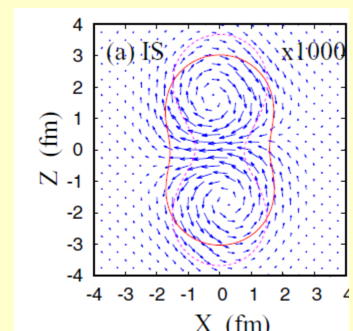
$^{10}Be = {}^{8}He + 2n$

Yoshiko Kanada-En'yo and Yuki Shikata
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

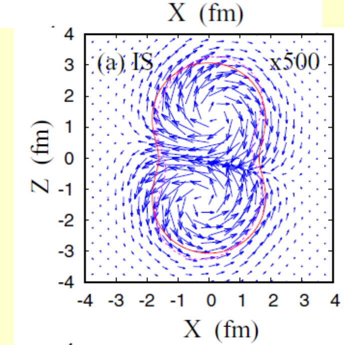
We studied dipole excitations in ^{10}Be based on an extended version of the antisymmetrized molecular dynamics, which can describe 1p-1h excitations and large amplitude cluster modes. Toroidal and compressive dipole operators are found to be good proves to separate the low-energy and high-energy parts of the isoscalar dipole excitations, respectively. Two low-energy 1^- states, the toroidal dominant 1_1^- state at $E \sim 8$ MeV and the $E1$ dominant 1_2^- state at $E \sim 16$ MeV, were obtained. By analysis of transition current densities, the 1_1^- state is understood as a toroidal dipole mode with exotic toroidal neutron flow caused by rotation of a deformed ^{6}He cluster, whereas the 1_2^- state is regarded as a neutron-skin oscillation mode, which are characterized by surface neutron flow with inner isoscalar flow caused by the surface neutron oscillation against the 2α core.







AMD



cluster GCM

the lowest dipole state $I^\pi K = 1^- 1_1$ is toroidal!

[21] J. Kvasil, V. O. Nesterenko, W. Kleinig, P.-G. Reinhard, and P. Vesely, Phys. Rev. C 84, 034303 (2011).
[22] A. Repko, P.-G. Reinhard, V. O. Nesterenko, and J. Kvasil, Phys. Rev. C 87, 024305 (2013).
[23] V. O. Nesterenko, J. Kvasil, A. Repko, W. Kleinig, and P.-G. Reinhard, Phys. At. Nucl. 79, 842 (2016).

Experimental perspectives

Which reaction is most suitable to observe TM?

What is TM signature to be used for unambiguous identification of TM?

(e,e') as the first choice

Here we meet the problem: impact of the magnetization current

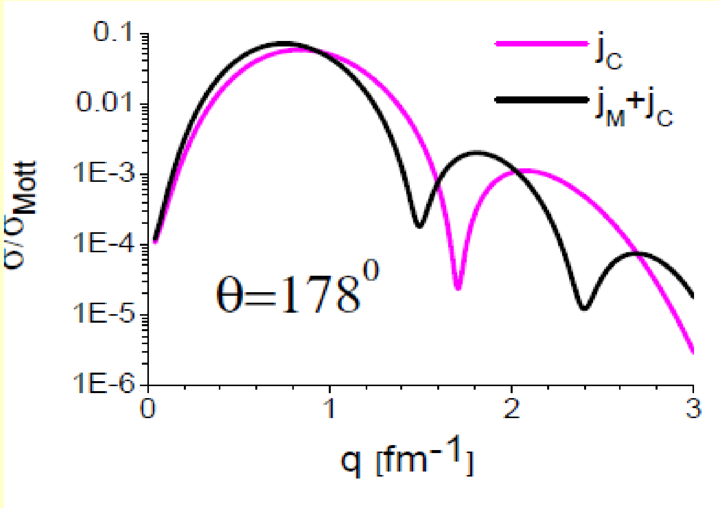
$$\hat{M}_{tor}(E1\mu) = \frac{1}{10\sqrt{2}c}\int d\vec{r}\,[r^3 + \frac{5}{3}r < r^2 >_0]\,\vec{Y}_{11\mu}(\hat{\vec{r}})\cdot[\vec{\nabla}\times\hat{\vec{j}}_{nuc}(\vec{r})]$$

Nuclear current

$$\hat{\vec{j}}_{nuc}(\vec{r}) = \frac{e\hbar}{m}\sum_{q=n,p}(\hat{\vec{j}}^{q}_{con}(\vec{r}) + \hat{\vec{j}}^{q}_{mag}(\vec{r}))$$

$$\hat{\vec{j}}^{q}_{con}(\vec{r}) = -ie^{q}_{eff}\sum_{k\ni q}\left(\delta(\vec{r}-\vec{r}_k)\vec{\nabla}_k - \overleftarrow{\nabla}_k\delta(\vec{r}-\vec{r}_k)\right)$$ → toroidal flow

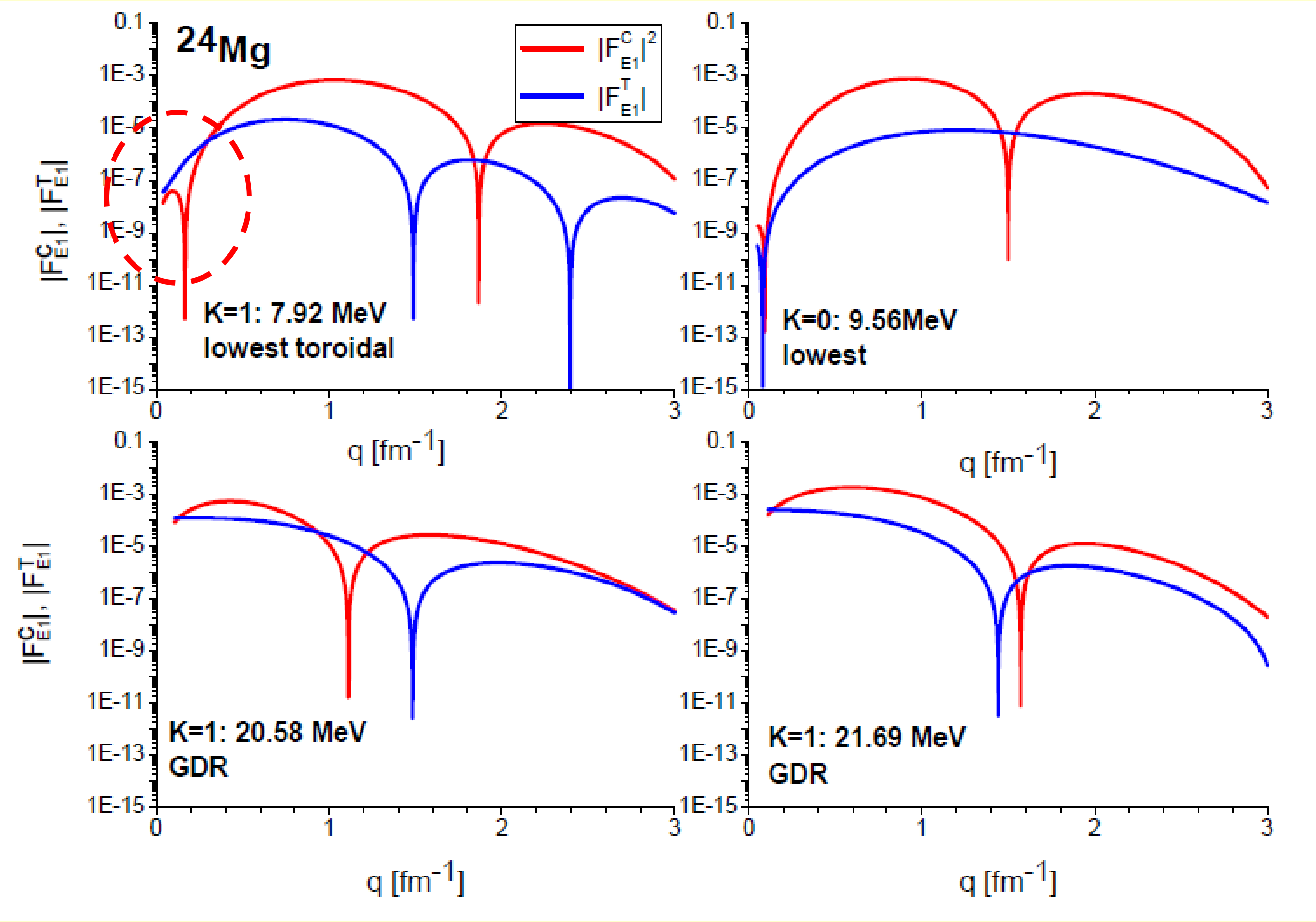
$$\hat{\vec{j}}^{q}_{mag}(\vec{r}) = \frac{g^q_s}{2}\gamma\sum_{k\ni q}\vec{\nabla}_k\times\hat{\vec{s}}_{qk}\delta(\vec{r}-\vec{r}_k), \qquad \gamma = 0.7$$



PWBA for 24Mg

Impact of $\vec{j}_M$ current is significant at $q > 1\ \mathrm{fm}^{-1}$, and makes toroidal effect unresolved.

(e,e'): Longitudinal $|F^C_{E1}|^2$ and transverse $|F^T_{E1}|^2$ form factors for different states in 24Mg



At low q, TS gives a specific diffraction minimum and $|F^T_{E1}|^2 > |F^C_{E1}|^2$

This could be the effect of the competition between:

- large IS and small IV fractions ⟵ H. Miska et al, PLB, **59**, 441 (1975).
- toroidal vortex and antivortex ⟵ **to be checked!**

Possible routs to observe the toroidal mode:

1) Indirect (CM → TM) excitation of TM in (α,α') through CM/TM coupling.

2) (e,e’), low-q-minimum

3) $(e,e'\gamma)$, $(\alpha,\alpha'\gamma)$ ⇒ scattering angle of the photon can depend on the nuclear flow.

4) Reactions with polarized projectiles/targets.

5) To inspect other TDR features:
(to search vortex and antivortex rotational bands, …).

Conclusions

★ Toroidal dipole resonance (TDR) is interesting in many aspects:

- still unique example of electric intrinsic vortical motion,
- TDR is a possible origin of PDR.

However TDR has problems with direct experimental observation.

★ We propose a new route: investigation of individual toroidal states (TS) in light nuclei. Light nuclei seem to be very promising for this aim. Interesting relations with a cluster structure.

General message:

TM example shows that modern experiment is yet unable to measure and identify electric intrinsic vortical excitations.

Nuclear vortical dynamics is still terra incognita. This fundamental problem is a challenge for modern theory and experiment.

Thank you for attention!