TOROIDAL MODE: FROM GIANT RESONANCE TO INDIVIDUAL STATES

V.O. Nesterenko

Joint Institute for Nuclear Research, Dubna, Moscow region, Russia

J. Kvasil,
Inst. of Particle and Nuclear Physics, Charles University, Praha , Czech Rep.

A. Repko
Inst. of Physics, Slovak Academy of Sciences, Bratislava, Slovakia

P.-G. Reinhard
Inst. of Theor. Physics II, University of Erlangen, Erlangen, Germany

COMEX6, Cape Town, South Africa, 29.10-02.11.2018

Motivation and content

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

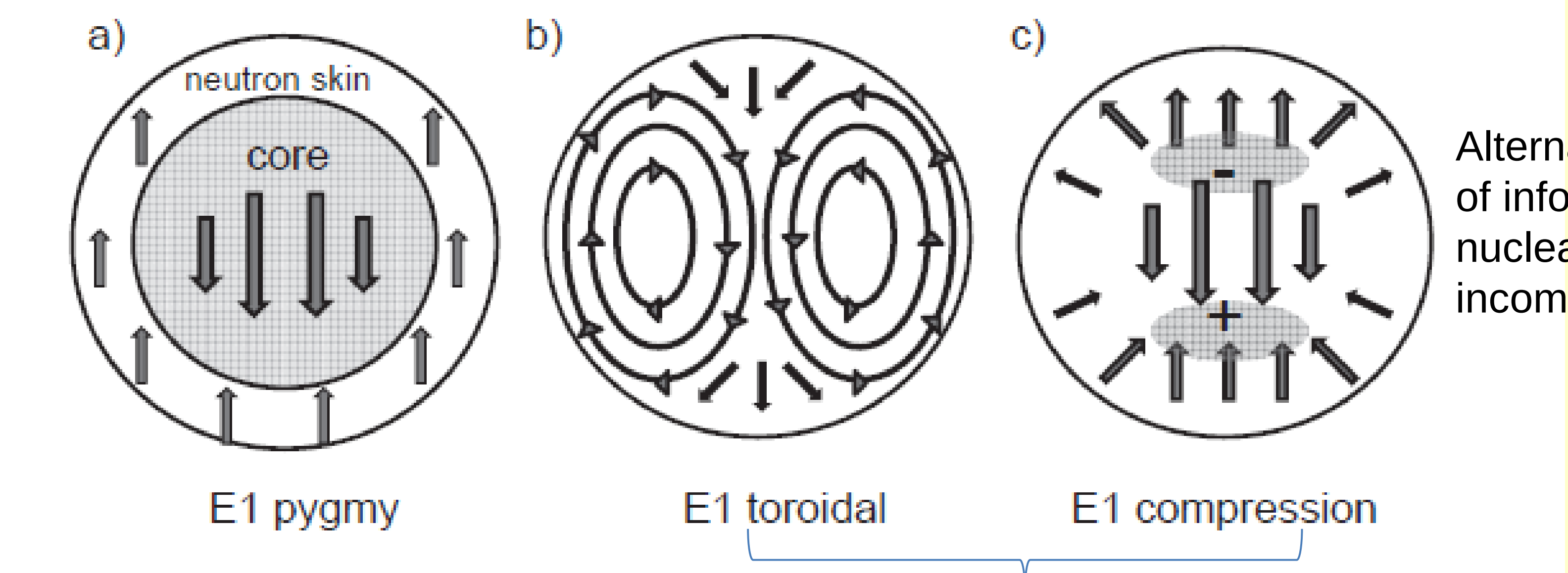
- Problems with TDR experiment: there are only indirect (α,α') data.

- New alternative way:
  recent calculations show that in light nuclei 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)

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:

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

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

$$\Downarrow$$

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

Toroidal and compression operators are coupled:

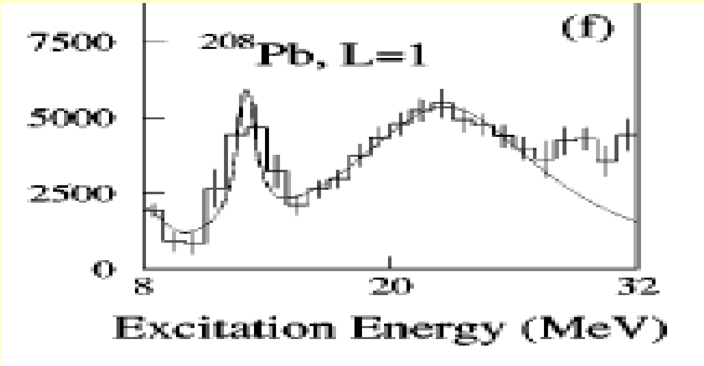
$$\hat{M}_{tor}(E1\mu) = -\frac{i}{2\sqrt{3}c}\int d\vec{r}\,\hat{\vec{j}}_{nuc}(\vec{r})\cdot\vec{\nabla}\times(\vec{r}\times\vec{\nabla})[r^3 - \frac{5}{3}r < r^2 >_0]\,Y_{1\mu}(\hat{\vec{r}})$$

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

Experiment: (α,α')

Familiar treatment → LE (toroidal) HE (compression)

^{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

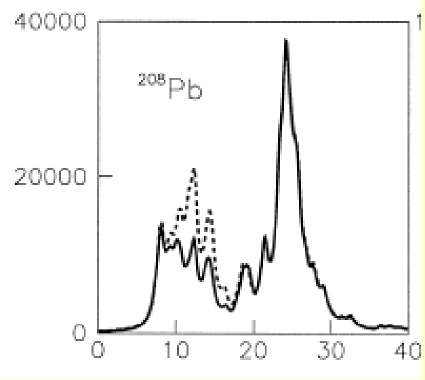
There are also exp ISGDR data in

^{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).



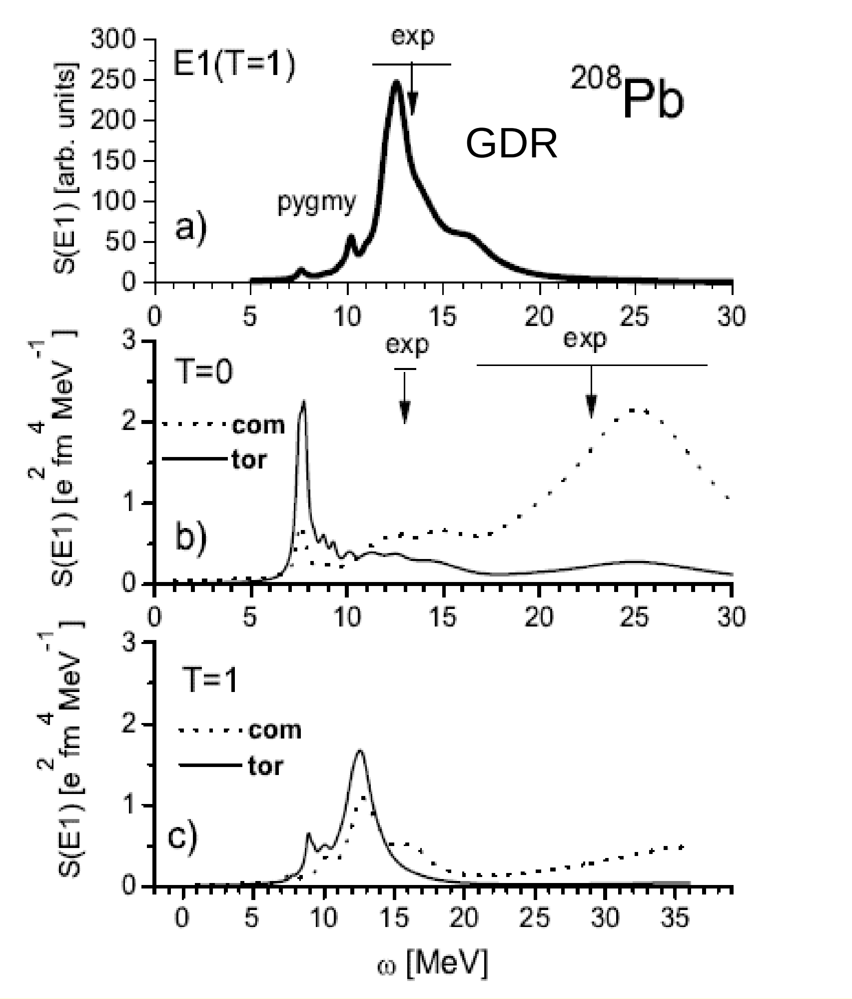
Perhaps Uchida observed at 10-17 MeV not TDR but CDR fraction coupled to TDR. Main TDR peak should lie lower at ~ 7-9 MeV.

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!

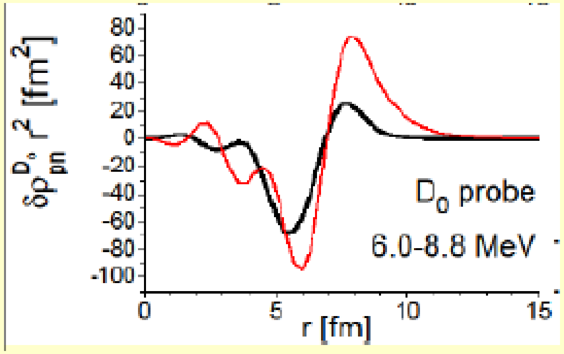
Strength functions SLy6

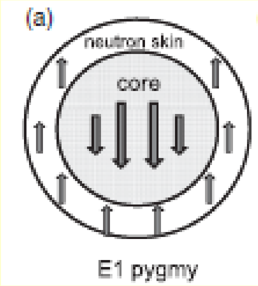
A. Repko, P.G. Reinhard, VON, J. Kvasil,
PRC, 87, 024305 (2013)



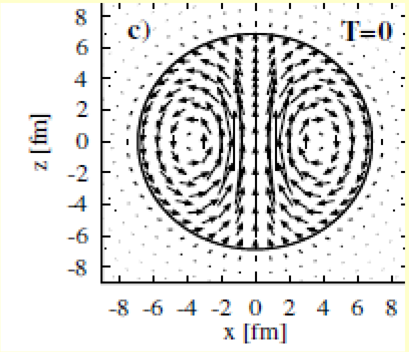
PDR region hosts TDR and CR!

Typical PDR transition density:

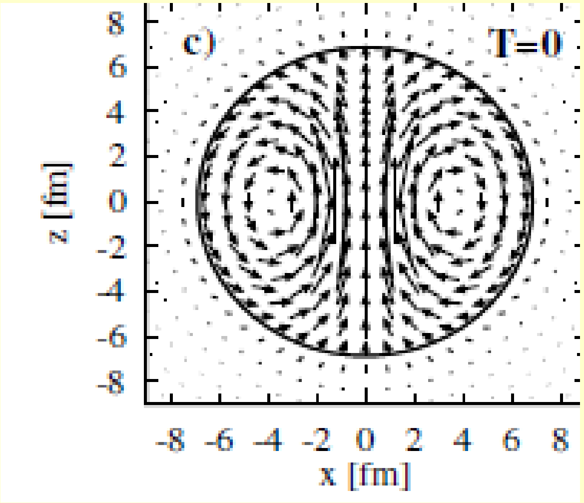




Nucleon current in the PDR region is mainly toroidal!

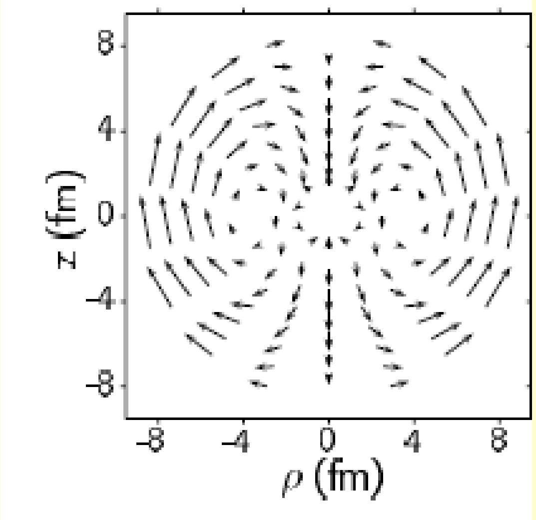


Skyrme RPA: 208Pb
Repko, P.-G. Reinhard, VON, J. Kvasil,
PRC, 87, 024305 (2013).

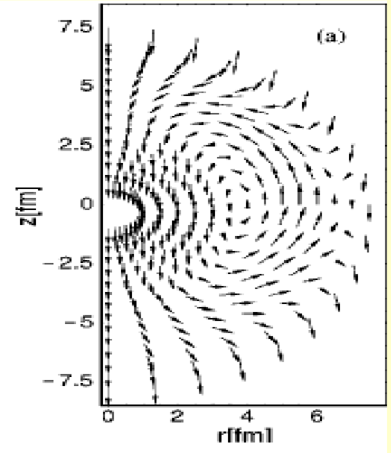


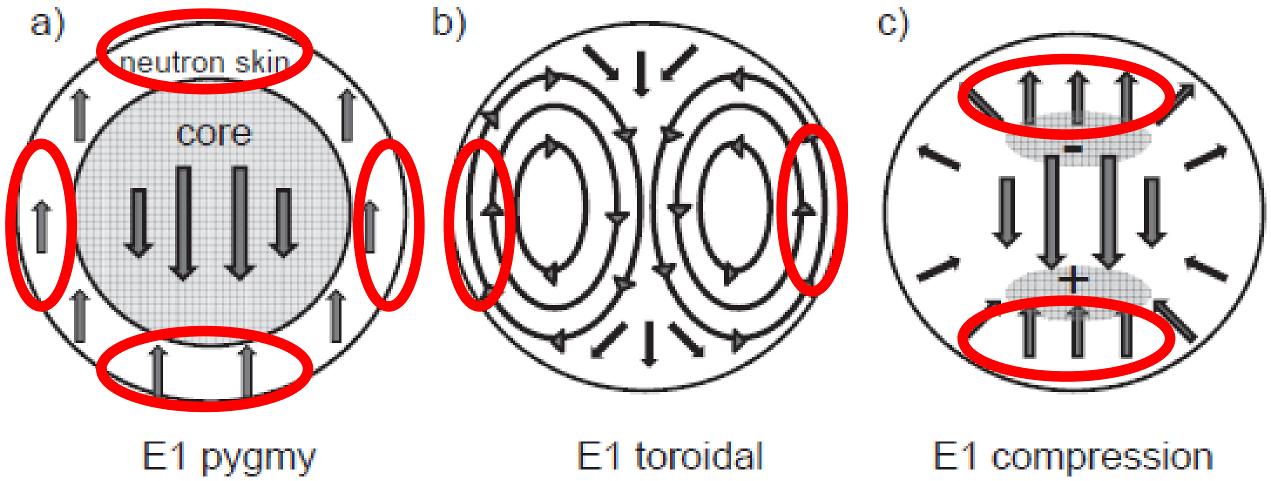
- Similar results for
  Ca, Ni, Zr, Sn, Sm, Yb, U

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



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





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.**

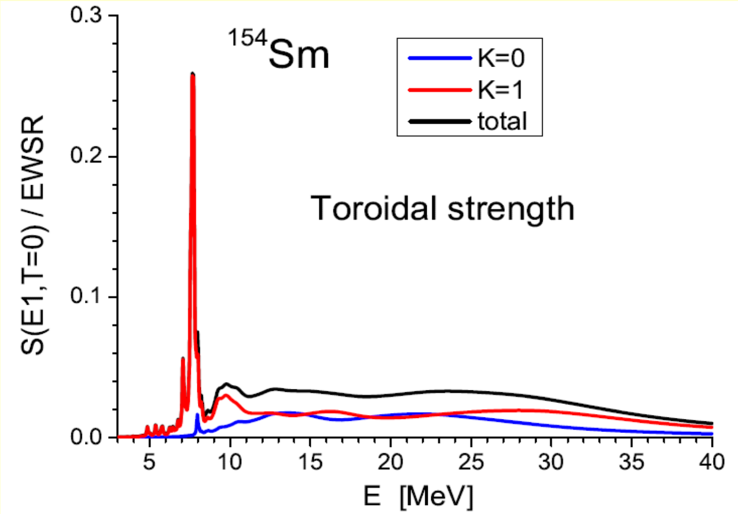
Deformation features of TDR

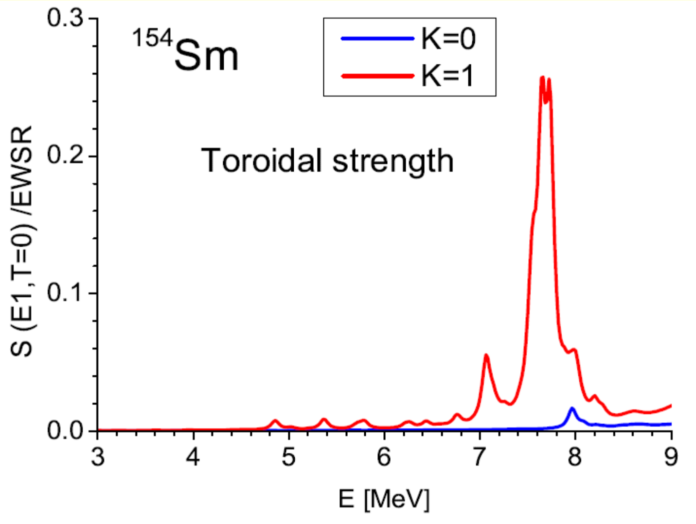
Skyrme QRPA, SLy6

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

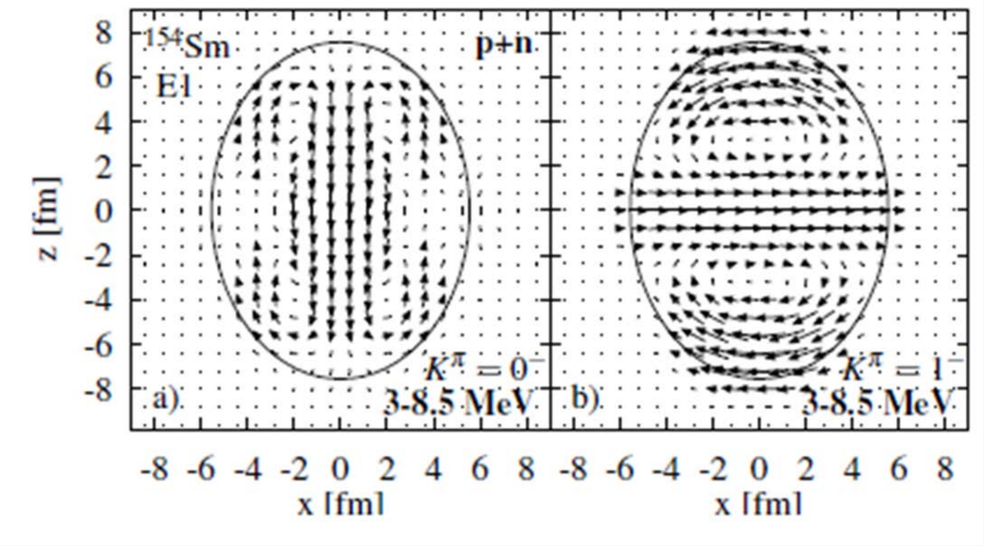
154Sm, SLy6 $\beta_2^{exp} = 0.339$

Energy-weighted strength functions





K=1 dominates !!!



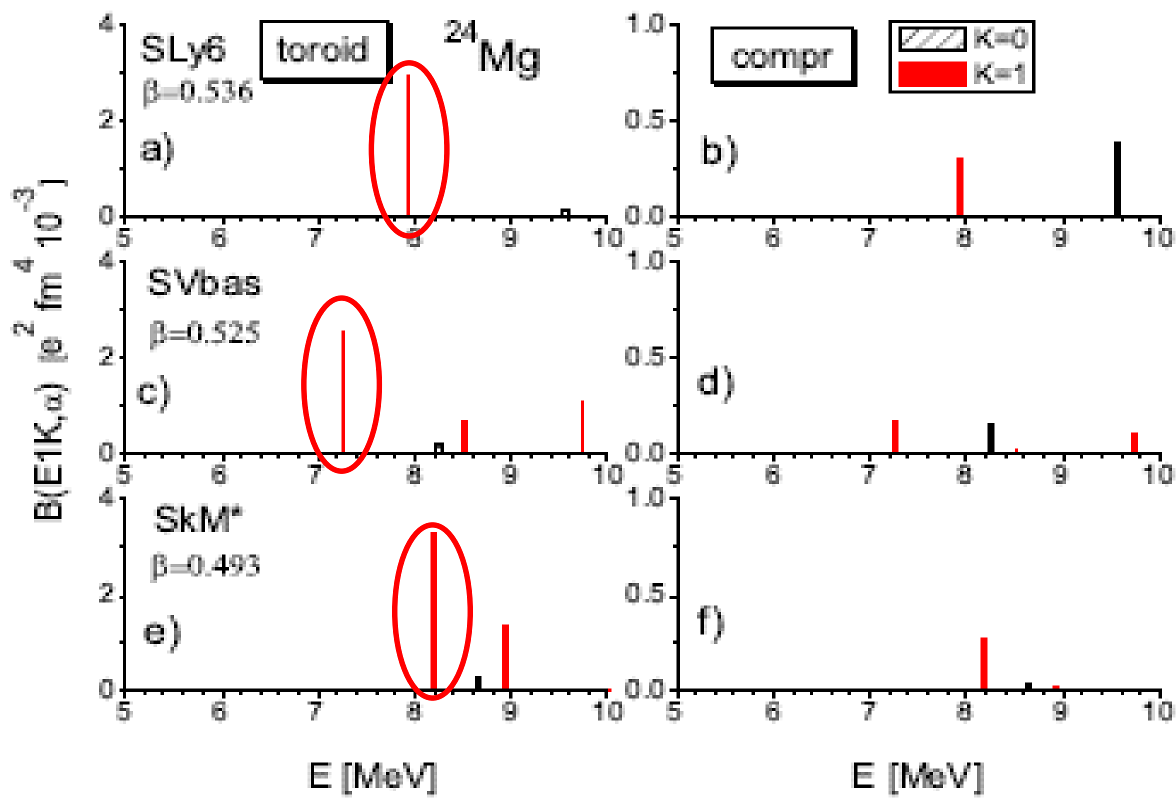
Similar results for other prolate nuclei.

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

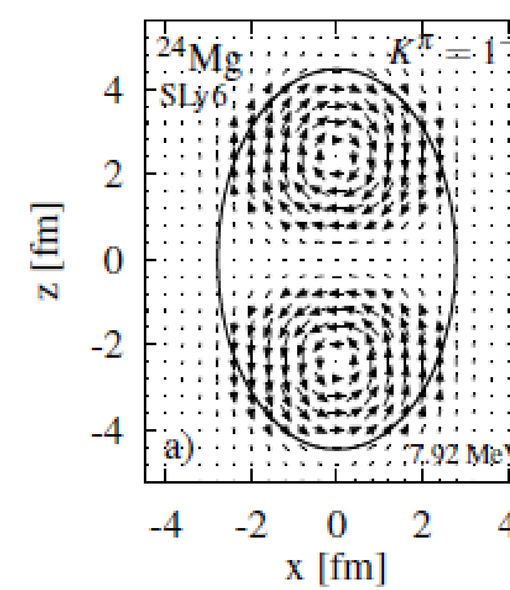
If prolate deformation is so important, then what we will get in nuclei with a huge axial deformation, like ^{24}Mg?

^{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*

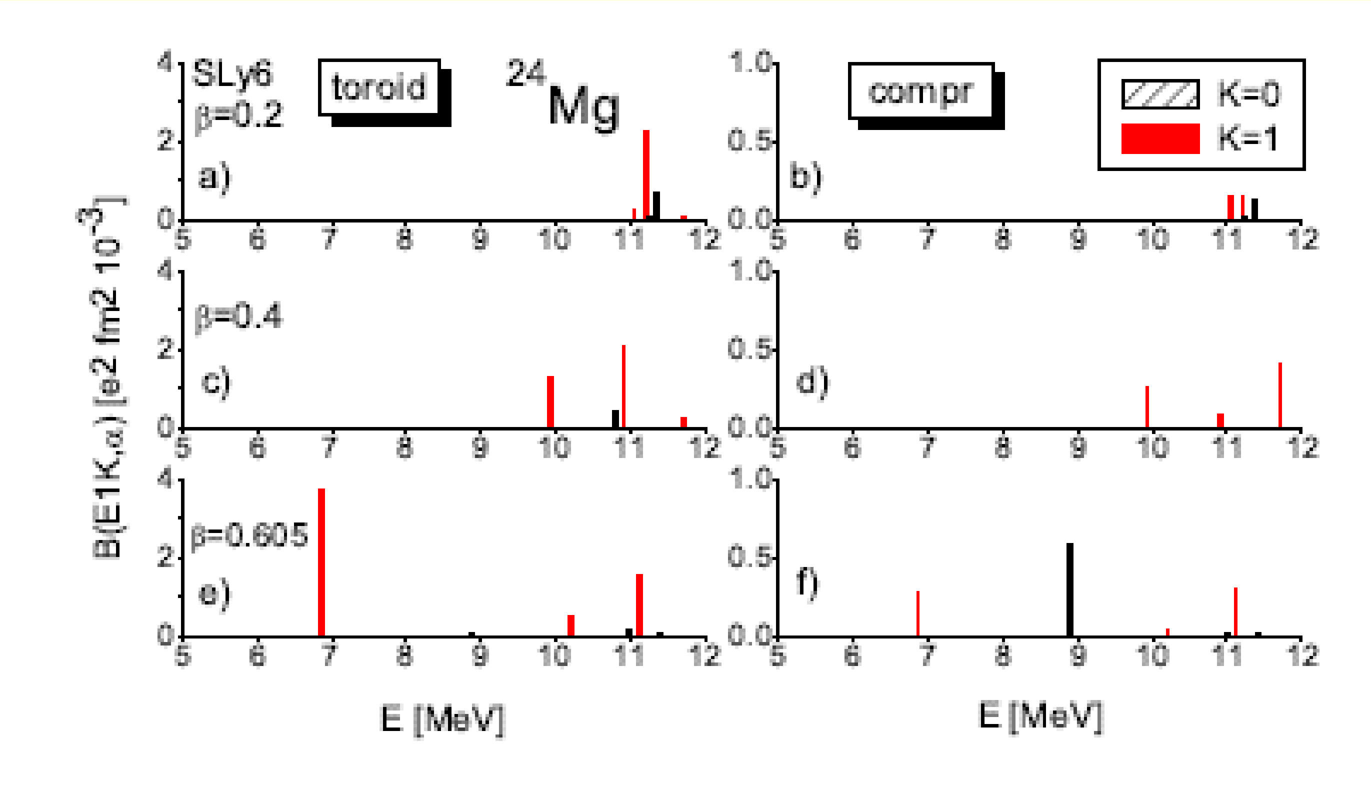


Persistence of the main result:
the **lowest** toroidal K=1 peak

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

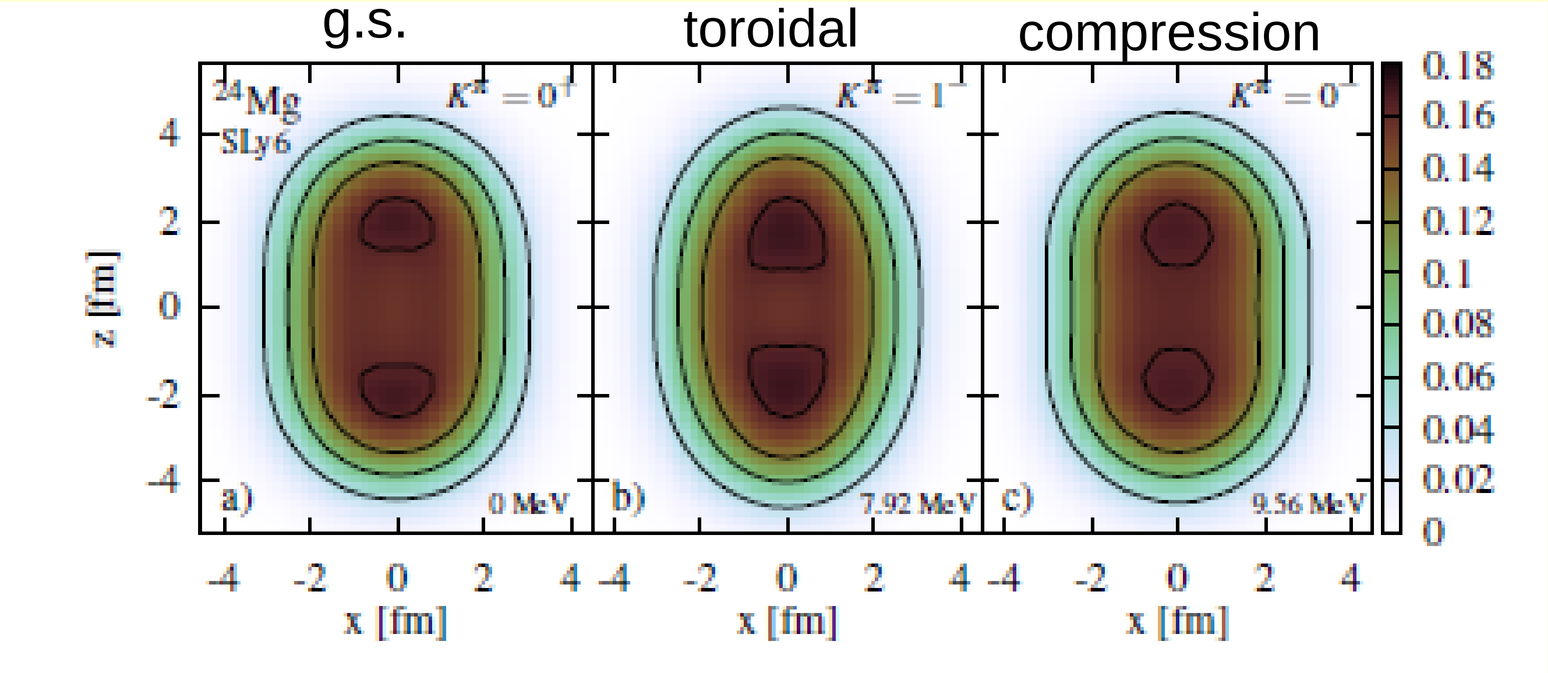
To get individual lowest TS, two rigorous requirements should be held:

- huge prolate deformations
- sparse low-energy spectrum

This can be realized just in light deformed nuclei

Relation to cluster structure of 24Mg

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



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 the vortex ring into vortex-antivortex pair.
- Toroidal flow looks as rotation of two clusters in the opposite direction.
  Appearance of specific vortical rotational bands?

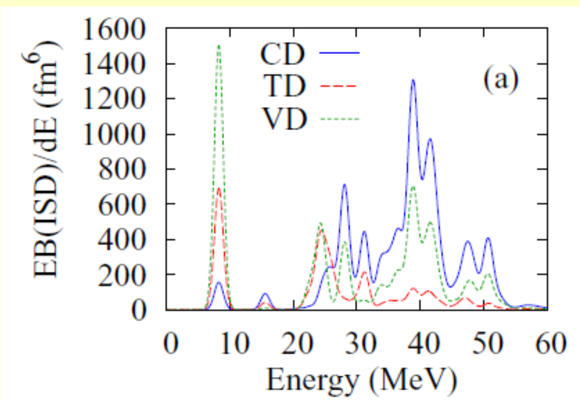
PHYSICAL REVIEW C 95, 064319 (2017)

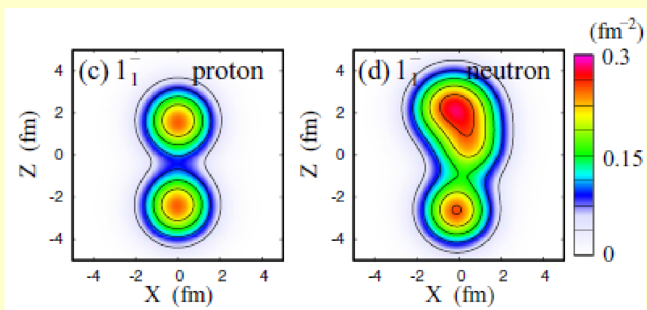
Toroidal, compressive, and $E1$ properties of low-energy dipole modes in ^{10}Be

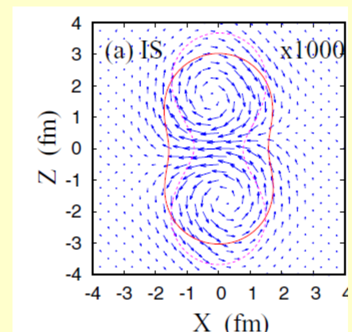
$^{10}Be = ^{8}He + 2n$

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

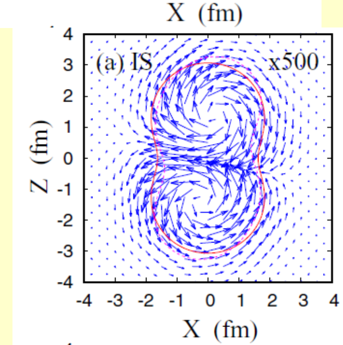
We studied dipole excitations in ^{10}Be based on an extended version of the antisymmetrized molecular dynamics, which can describe 1p-1h excitations and large amplitude cluster modes. Toroidal and compressive dipole operators are found to be good proves to separate the low-energy and high-energy parts 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).

How to check experimentally these theoretical predictions?

What is the suitable reaction to observe TM in experiment?

Which signature can be used for unambiguous identification of TM?

What about (e,e')?

Here we meet the problem: impact of the magnetization current

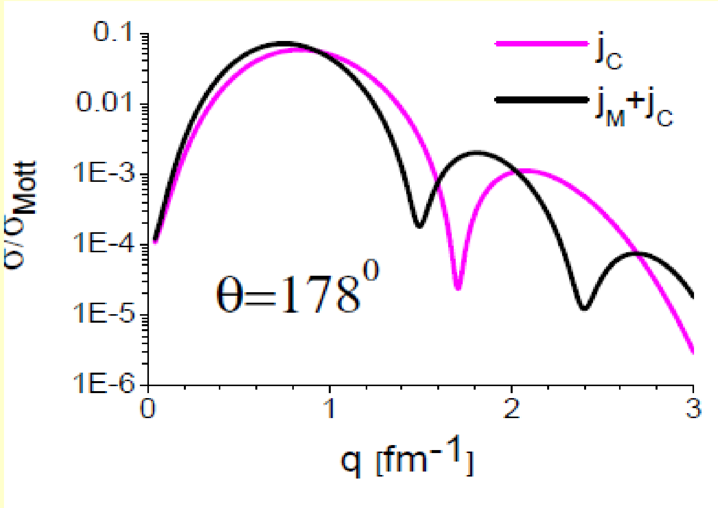
$$\hat{M}_{tor}(E1\mu) = \frac{1}{10\sqrt{2}c}\int d\vec{r}\,[r^3 + \frac{5}{3}r < r^2 >_0]\,\vec{Y}_{11\mu}(\hat{\vec{r}})\cdot[\vec{\nabla}\times\hat{\vec{j}}_{nuc}(\vec{r})]$$

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 $q > 1\ fm^{-1}$, and makes toroidal effect unresolved.

Possible routs to observe the toroidal mode:

1) Indirect (CM $\longrightarrow$ TM) excitation of TM in (α,α') using the CM/TM coupling.

2) $(e,e'\gamma)$ $\longrightarrow$ scattering angle of the photon can depend on the nuclear flow.

3) Using polarizability: toroidal flow can polarize the outcoming electron.

4) To use not current distributions but other TDR features (like in the case of the scissors M1 mode).

The search of TM is a part of the fundamental problem.
On the TM example, we see that modern experiment is not yet able to measure and identify electric intrinsic vortical excitations.

Nuclear vortical dynamics is still terra incognita.

Conclusions

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

- The quest of TM is a part of the general fundamental problem: ability of modern theory and experiment to explore vortical nuclear flow.

Thank you for attention!