Exotic Vortical Excitations in Nuclei

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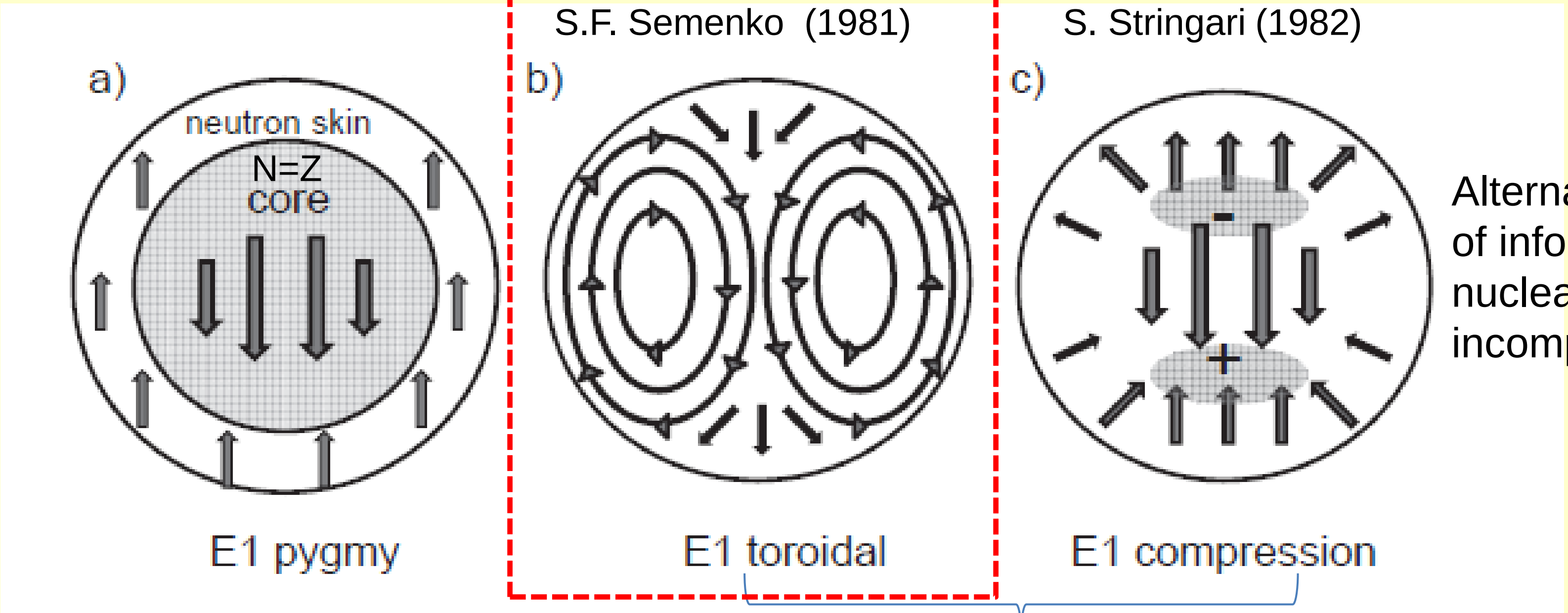
Семинар им. Б.С. Ишханова «Фотоядерные исследования: Состояние и перспективы», НИИЯФ МГУ, 26.10.23

Exotic dipole resonances (beyond IV GDR)

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 isoscalar E1excitation channel
(due to suppression of dominant E1(T=1) motion)

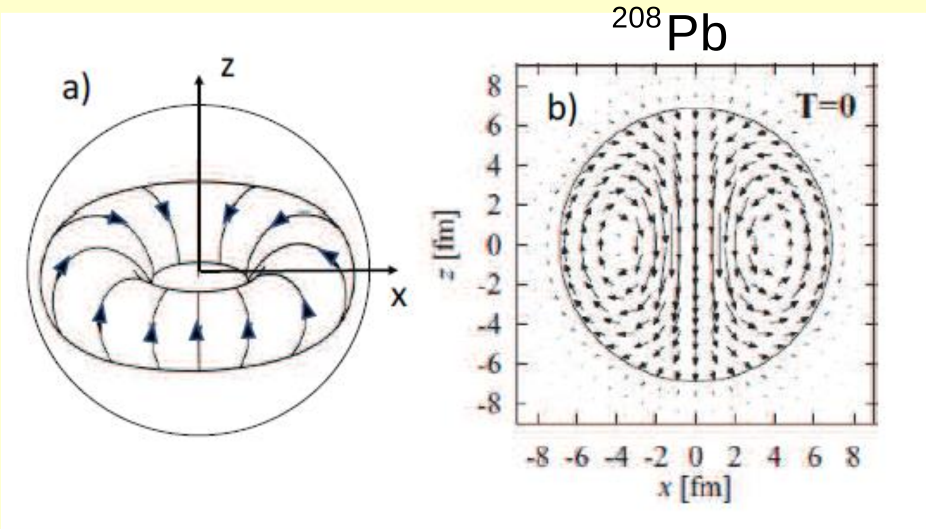
irrotational | vortical | irrotational

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

- 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).

Nuclear toroidal flow as a vortical ring (VR)

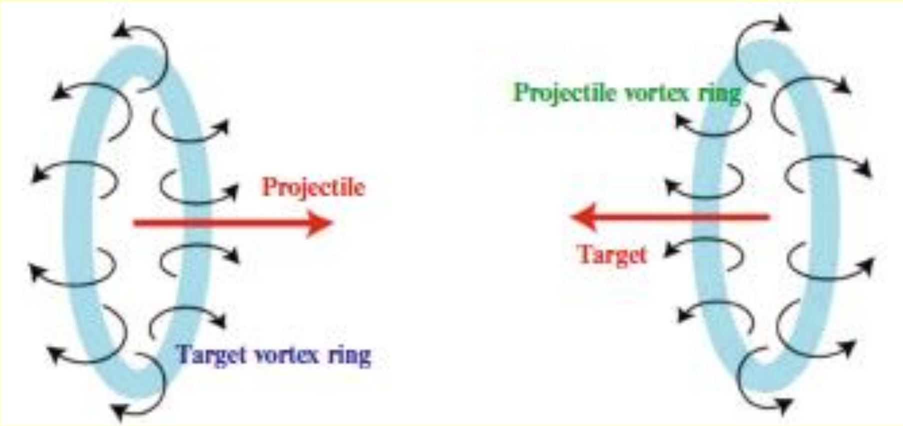


Toroidal dipole resonance (TDR) in nuclei:
- confined vortical flow
- spinning-like oscillations on the torus surface
- vortex ring at each oscillation step
- unique example of intrinsic E1 vortical excitation

S.F. Semenko, Sov.J. Nucl. Phys. 34 356 (1981)

………..

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



Central heavy ion collisions:
- collision energies 4-30 GeV
- two vortex rings
- spinning of nucleons

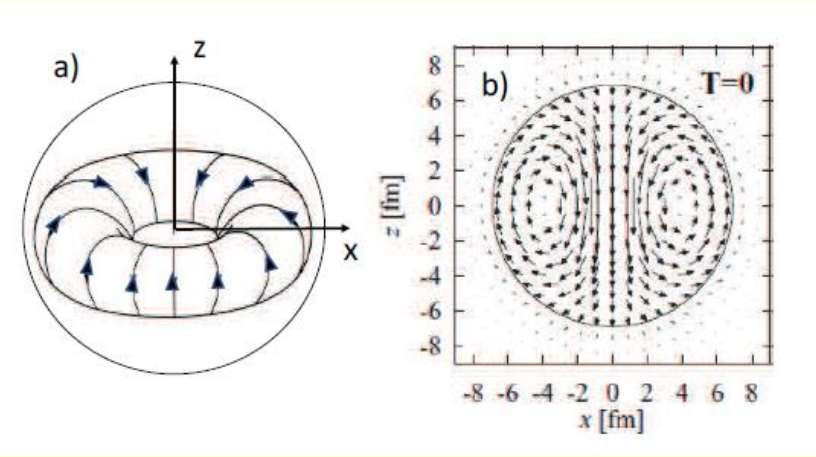
Yu.B. Ivanov, V.D. Toneev and A.A. Soldatov, Phys. At. Nucl. **83**, 179 (2020)

Both vortical flows are Hill's vortex rings

Hill's vortex ring (HIR)

- was suggested by Hill in 1894 as one of the exact solutions of Euler equations
- is one of the most simple cases of a vortical flow caused by nuclear turbulence
- this is a vortex ring
- very stable, may not consume the external energy
- is very common in liquids and gases but rarely noticed unless the motion of the fluid is revealed by suspended particles (smoke rings)

colored by tobacco particles
and so are visible



Each listener of my talk permanently produces (invisible) Hill's vortex rings in the surrounding air when breathing out!

Hill's vortex is very general phenomenon. It must exist in nuclei as TDR but still was not safely observed. TDR is a general phenomenon in atomic nuclei, independently on nuclear size, Z/A ratio and nuclear shape.

Unlike a conventional hydrodynamics, nuclear TDR is caused not by turbulence but by mean-field vortical flow of nucleons.

Being vortical, TDR does not contribute to the continuity equation (CE)

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

So TDR is a remarkable example of nuclear dynamics beyond CE.

This is still a challenge to observe vortical excitations in general and TDR in particular in nuclei So the experimental search of TDR is a useful first step in solution of this general experimental problem.

TDR should exist in PDR energy region near nuclear thresholds. It can affect E1 strength in this energy range. So it can be important for nucleosynthesis and astrophysical problems.

Interesting crossover with other areas of physics (neutron stars, heavy-ion collisions, metamaterials, …).

Individual toroidal states can affect manifestations of clustering in light nuclei.

Toroidal vortical mode appears in:

★ nuclear current density

Following theorems of Helmholtz and Chandrasekhar/Moffat, the current distribution can be decomposed as

V.M. Dubovik and A.A. Cheshkov, Sov. J. Part. Nucl. v.5, 318 (1975).

$$\vec{j}(\vec{r}) = \vec{\nabla}\phi(\vec{r}) + \vec{\nabla}\times[\vec{r}\psi(\vec{r})] + \vec{\nabla}\times\vec{\nabla}\times[\vec{r}\chi(\vec{r})]$$

electric moments — magnetic moments — electric **toroidal** moments

E1 GDR, compression

transversal (magnetic and electric toroidal moments)

★ Multipole electric operator (probe external field) :

$$\hat{M}(Ek\lambda\mu) = \frac{(2\lambda+1)!!}{ck^{\lambda+1}}\sqrt{\frac{\lambda}{\lambda+1}}\int d\vec{r}\;\; \hat{\vec{j}}_{nuc}(\vec{r})\cdot[\vec{\nabla}\times(\vec{r}\times\vec{\nabla})\,(j_\lambda(kr)Y_{\lambda\mu})]$$

$$j_\lambda(kr) = \frac{(kr)^\lambda}{(2\lambda+1)!!}[1 - \frac{(kr)^2}{2(2\lambda+3)} + \ldots]$$

So, the toroidal operator is the second order term in long-wave expansion of the electric operator

$$\hat{M}(Ek\lambda\mu) = \hat{M}(E\lambda\mu) + k\hat{M}_{tor}(E\lambda\mu)$$

$$\hat{M}(E\lambda\mu) = \int d\vec{r}\,\rho(\vec{r})r^\lambda Y_{\lambda\mu} \longleftarrow$$

standard electric operator
In long wave approximation

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

Toroidal E1 operator:

$$\hat{M}_{tor}(E1\mu) = \frac{1}{10\sqrt{2}c} \int d\vec{r}\, [r^3 + \frac{5}{3} r \langle r^2 \rangle_0]\, \vec{Y}_{11\mu}(\hat{\vec{r}}) \cdot [\vec{\nabla} \times \hat{\vec{j}}_{nuc}(\vec{r})]$$

cmc — $\frac{5}{3} r \langle r^2 \rangle_0$

mainly vortical flow — $\vec{\nabla} \times \hat{\vec{j}}_{nuc}(\vec{r})$

Compression E1 operator:

$$\hat{M}_{com}(E1\mu) = -\frac{i}{10c} \int d\vec{r}\, [r^3 - \frac{5}{3} r \langle r^2 \rangle_0] Y_{1\mu}\, [\vec{\nabla} \cdot \hat{\vec{j}}_{nuc}(\vec{r})]$$

irrotational flow — $\vec{\nabla} \cdot \hat{\vec{j}}_{nuc}(\vec{r})$

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

⇓

$$\hat{M}'_{com}(E1\mu) = \int d\vec{r}\, \hat{\rho}(\vec{r})\, [r^3 - \frac{5}{3} r \langle r^2 \rangle_0] Y_{1\mu}$$

Toroidal and compression operators are coupled:

$$\hat{M}_{tor}(E1\mu) = -\frac{i}{2\sqrt{3}c} \int d\vec{r}\, \hat{\vec{j}}_{nuc}(\vec{r}) \cdot \vec{\nabla} \times (\vec{r} \times \vec{\nabla}) [r^3 - \frac{5}{3} r \langle r^2 \rangle_0]\, Y_{1\mu}(\hat{\vec{r}})$$

A. Repko, VON, J. Kvasil and P.-G. Reinhard, EPJA, 55, 242 (2019)

Origin of E1 vortial toroidal strength

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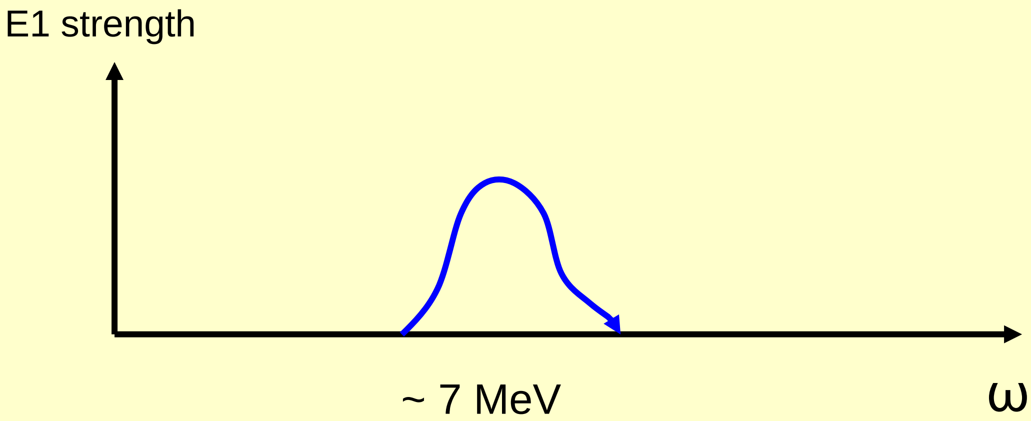
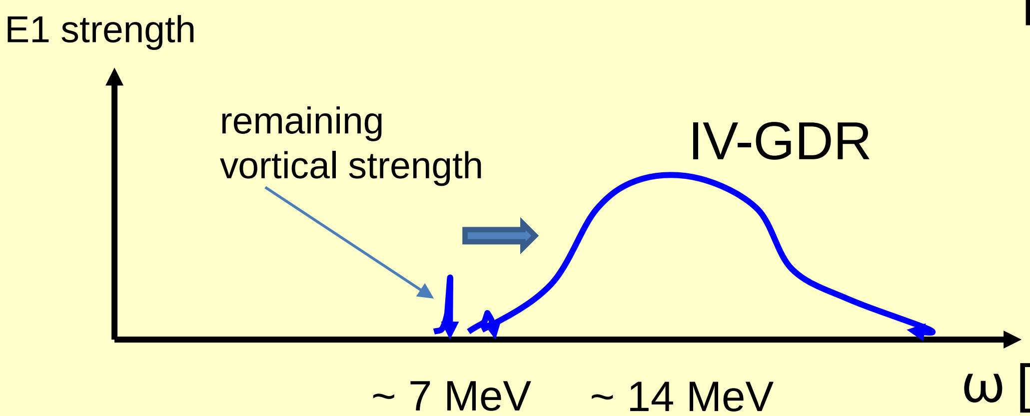
E1 toroidal strength must exist in all nuclei at the energy ~ E($\Delta N = 1$).



$H = H_{sp}$

1ph E1 strength from $\Delta N = 1$ dipole transitions
Strength is mainly irrotational
Vortical fraction is small



$H = H_{sp} + H_{res}$

IV residual interaction upshifts the irrotational E1 strength to form GDR but leaves at 7 MeV the vortical (toroidal) strength.

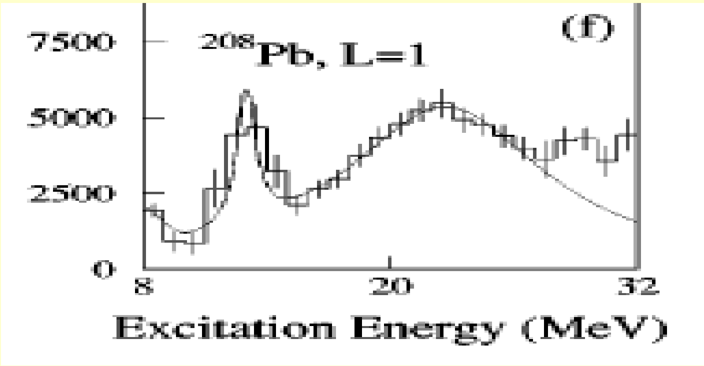
So TDR is indeed a general feature of atomic nuclei

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)



There are also exp ISGDR data in

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

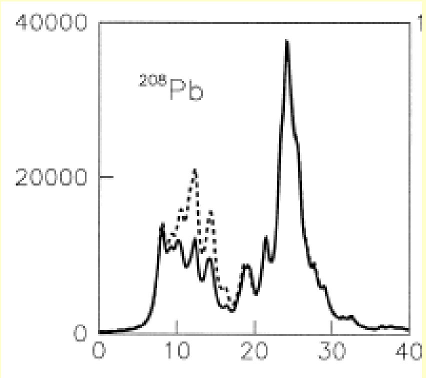
TDR

CDR

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

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);



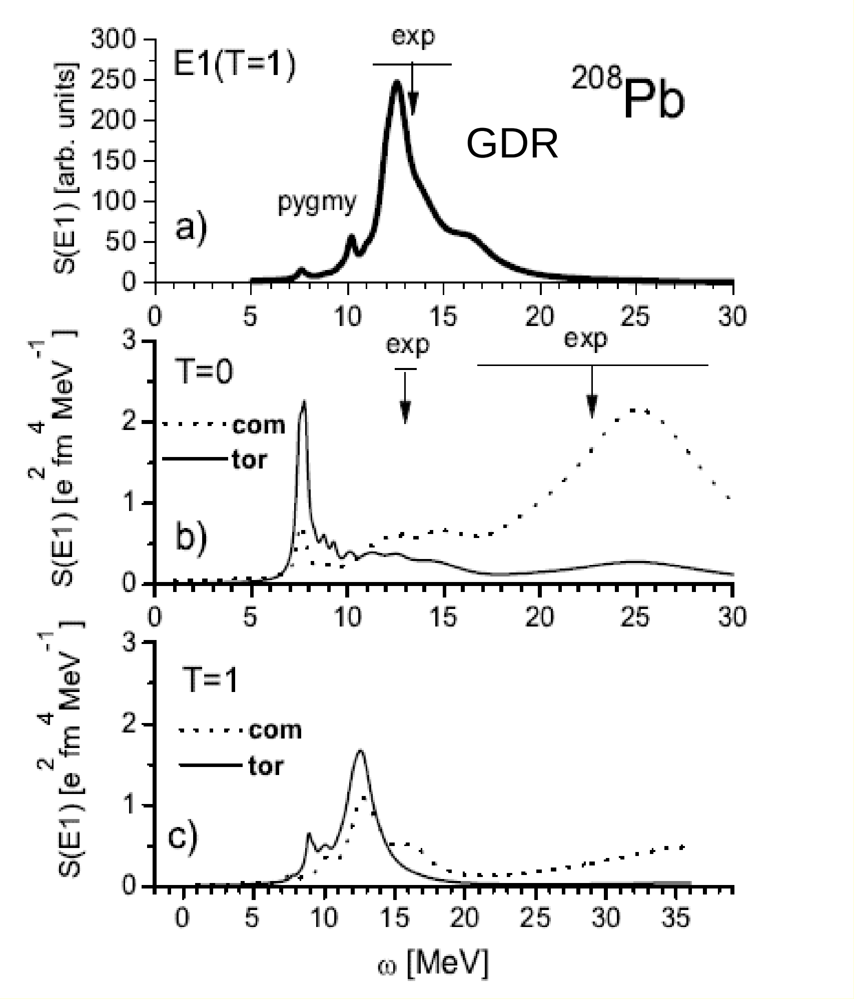
Perhaps Uchida observed at 10-17 MeV not TDR but CDR fraction coupled to TDR. Main TDR peak should lie lower at ~ 7-9 MeV. The direct observation of TDR in (α,α') can be disputed in general since (α,α') is mainly determined by transition density while toroid mainly depends on the vortical transition current.

NEED IN NEW EXPERIMENTS!

Skyrme QRPA calculations

Strength functions

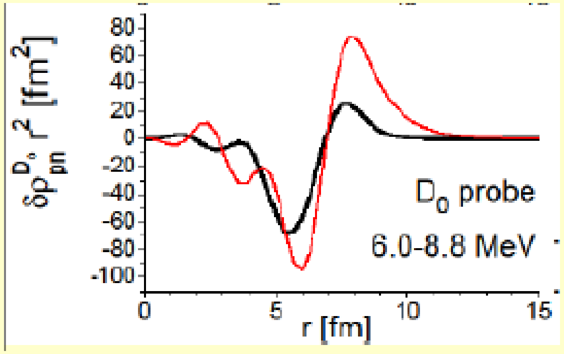
SLy6

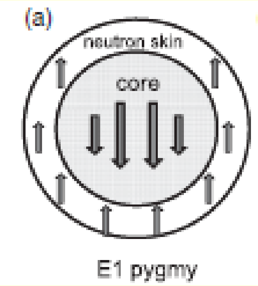


A. Repko, P.G. Reinhard, VON, J. Kvasil, PRC, 87, 024305 (2013)

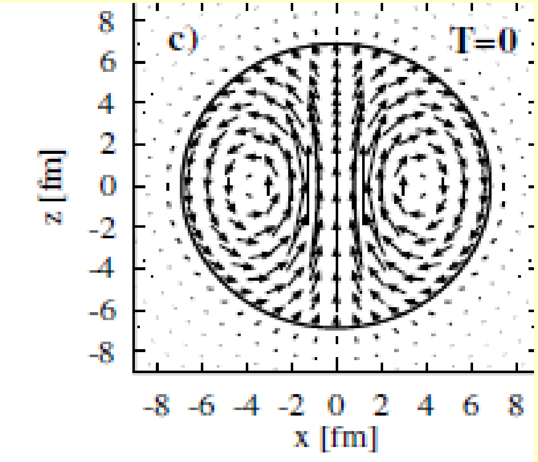
PDR region hosts TDR and CR!

Typical PDR transition density:





Nucleon current in the PDR region is mainly toroidal!



Individual toroidal states in light nuclei

PHYSICAL REVIEW LETTERS **120**, 182501 (2018)

Individual Low-Energy Toroidal Dipole State in ^{24}Mg

V. O. Nesterenko,[1*] A. Repko,[2] J. Kvasil,[3] and P.-G. Reinhard[4]

[1]*Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, Moscow region 141980, Russia*

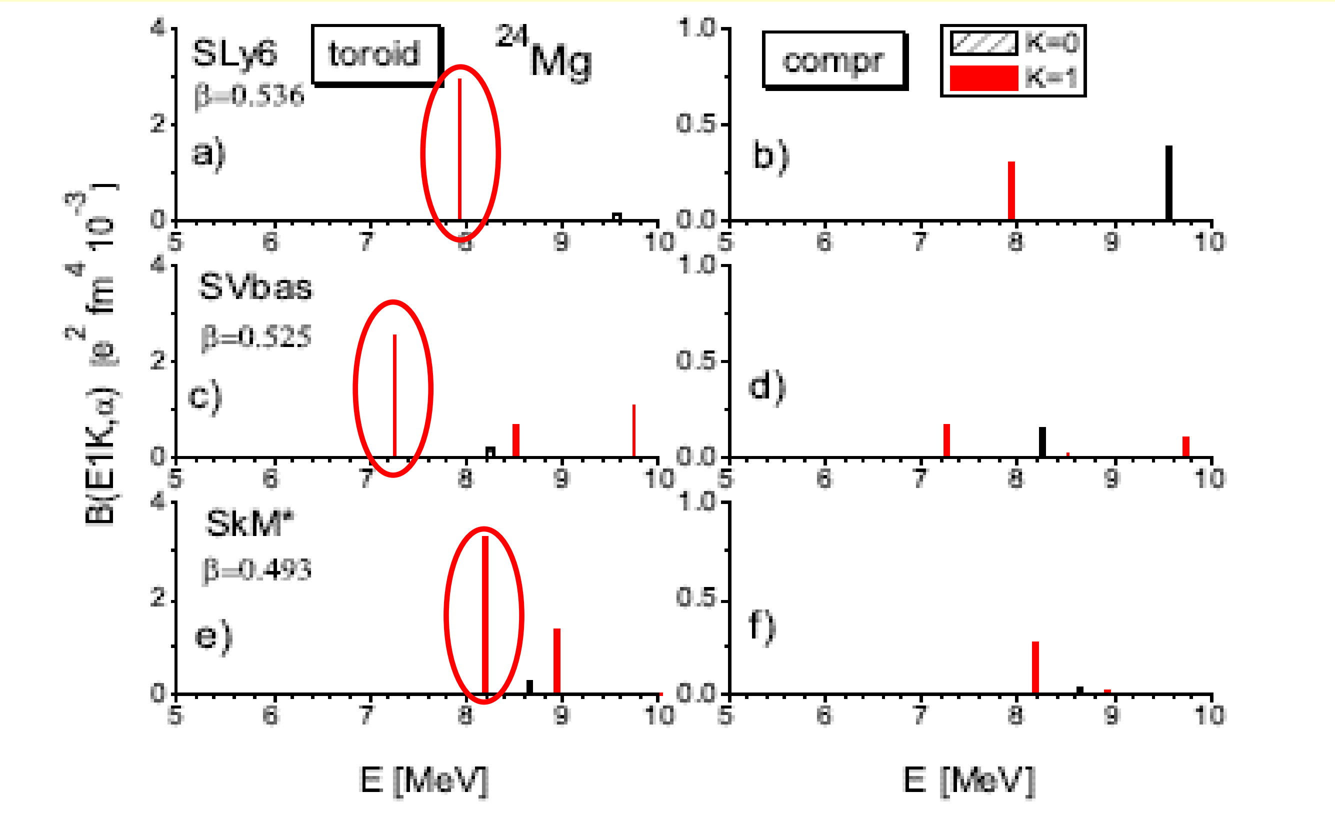
[2]*Department of Nuclear Physics, Institute of Physics SAS, 84511 Bratislava, Slovakia*

[3]*Institute of Particle and Nuclear Physics, Charles University, CZ-18000 Prague, Czech Republic*

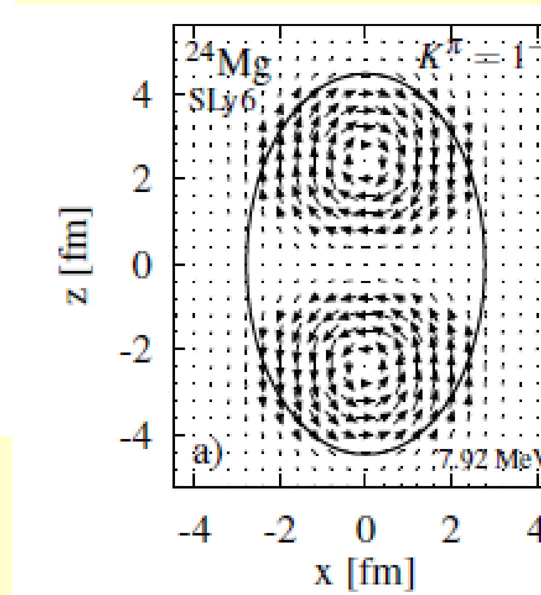
[4]*Institut für Theoretische Physik II, Universität Erlangen, D-91058 Erlangen, Germany*

^{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!

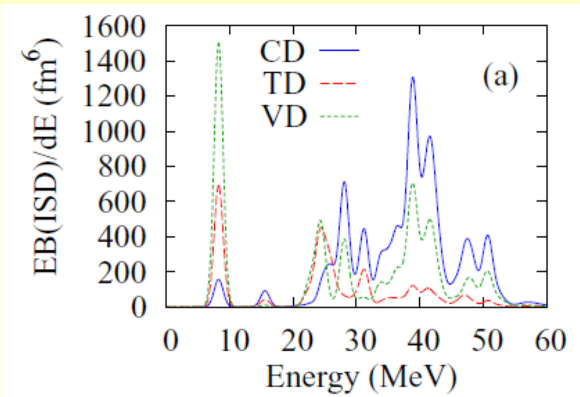
PHYSICAL REVIEW C 95, 064319 (2017)

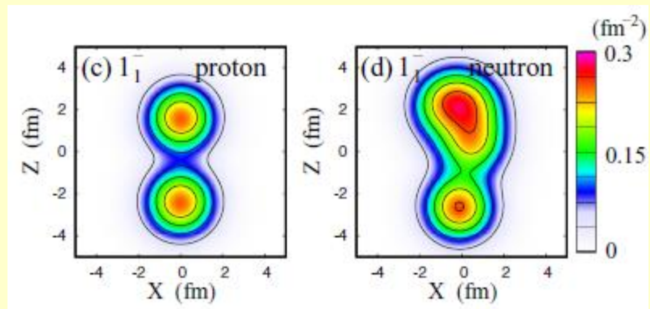
Toroidal, compressive, and $E1$ properties of low-energy dipole modes in ^{10}Be

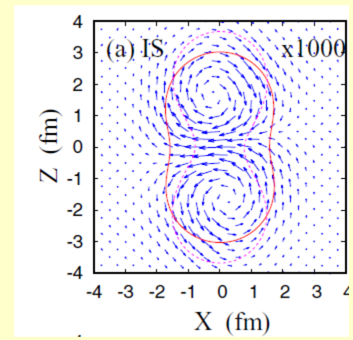
Yoshiko Kanada-En'yo and Yuki Shikata
Department of Physics, Kyoto University, Kyoto 606-8502, Japan

^{10}Be=^{6}He+α

Antisymmetrized molecular dynamics + generator coordinate method (AMD+GCM)
Cluster degrees + mean field







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

Y. Kanada-En'yo, Y. Shikata, and H. Morita, Phys. Rev. C 97, 014303 (2018)
Y. Kanada-En'yo and H. Horiuchi, Front. Phys. 13, 132108 (2018)
Y. Kanada-En'yo, Y. Shikata, and H. Morita, PRC 97, 014303 (2018)
Y. Shikata, Y. Kanada-En'yo, and H.Morita, Prog. Theor. Exp. Phys. **2019**, 063D01 (2019).
Y. Kanada-En'yo and Y. Shikata, Phys. Rev. C 100, 014301 (2019).
Y. Shikata and Y. Kanada-En'yo, PRC, 103, 034312 (2021).
Y. Chiba, Y. Kanada-En'yo, and Y. Shikata, arXiv:1911.08734.

In AMD+GCM, toroidal states were found in ^{10}Be, ^{12}C, ^{16,18}O, ^{24}Mg

Interplay of cluster and vortical modes:

General fundamental problem:

modern theory and experiment are not yet able to propose reliable ways for identification of intrinsic vortical modes. This fundamental problem is still unresolved. The search of E1 toroidal mode could be the first step in this direction.

Search of TDR in (e,e')

(e,e'): PWBA cross section

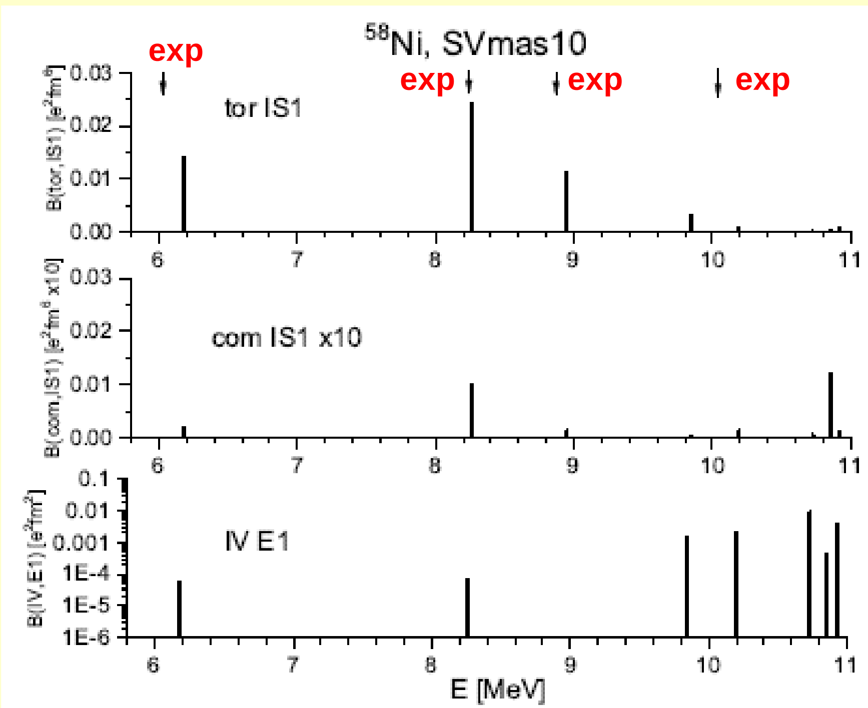
$$\sigma_{PWBA}(\theta,q)=\sigma_{Mott}(\theta,E_i)f_{rec}\{|F_E^C(q)|^2+(\frac{1}{2}+tg^2(\frac{\theta}{2})[|F_E^T(q)|^2+|F_M^T(q)|^2\}$$

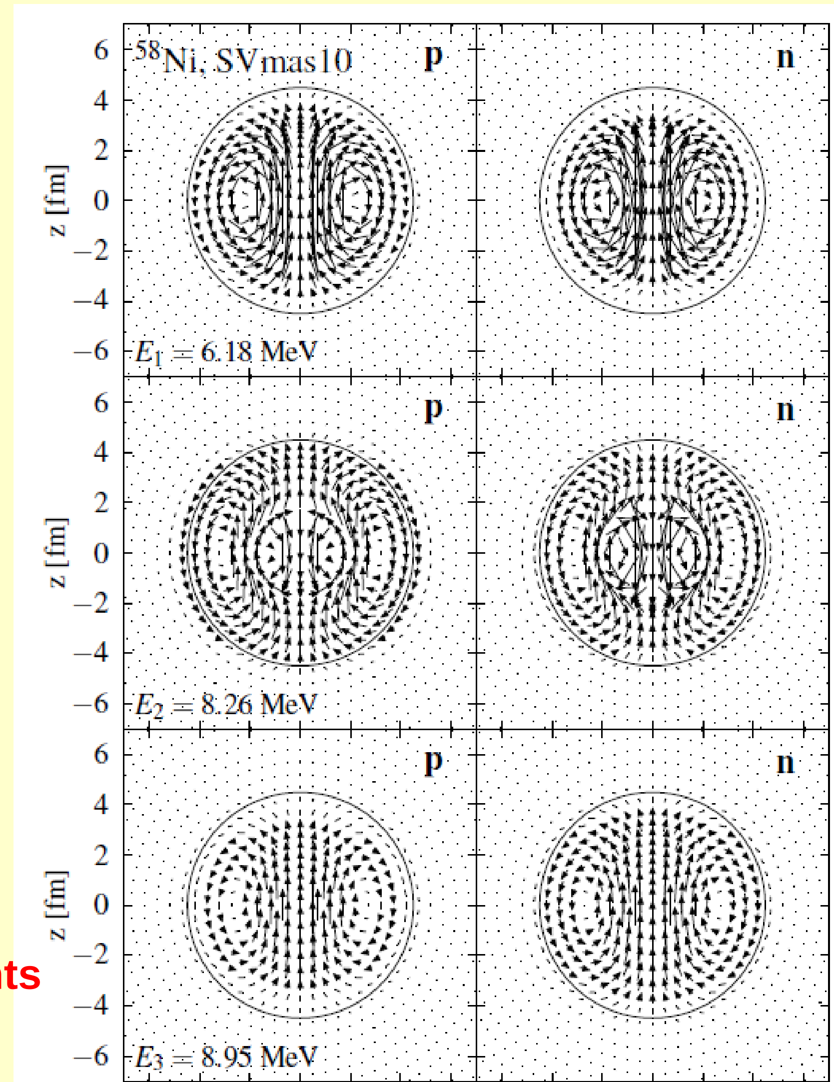
V.O. Nesterenko et al, PRC 100, 064302 (2019).

Recent results: Toroidal E1 states in spherical 58Ni

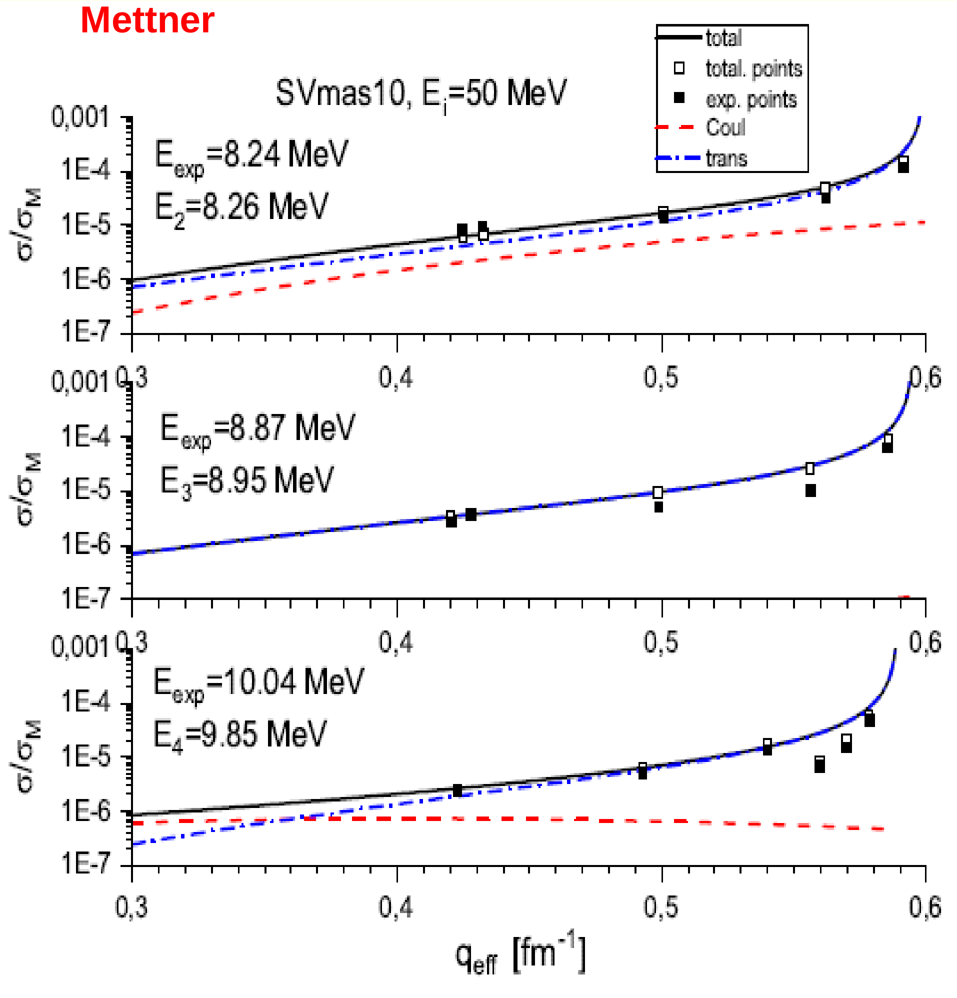
(e,e') experiments: W. Mettner, A. Richter et al, Nucl. Phys. A473, 160 (1987), Reitz
P. von Neumann Cosel (TU, Darmstadt) :

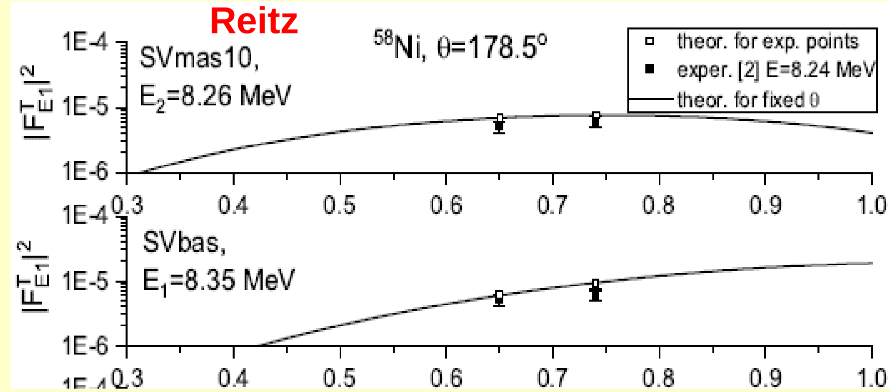
- large transversal form factors for some low-energy E1 states.
- exp. data from (g,g'), (p,p'), (α,α')
- to check if these states are toroidal?

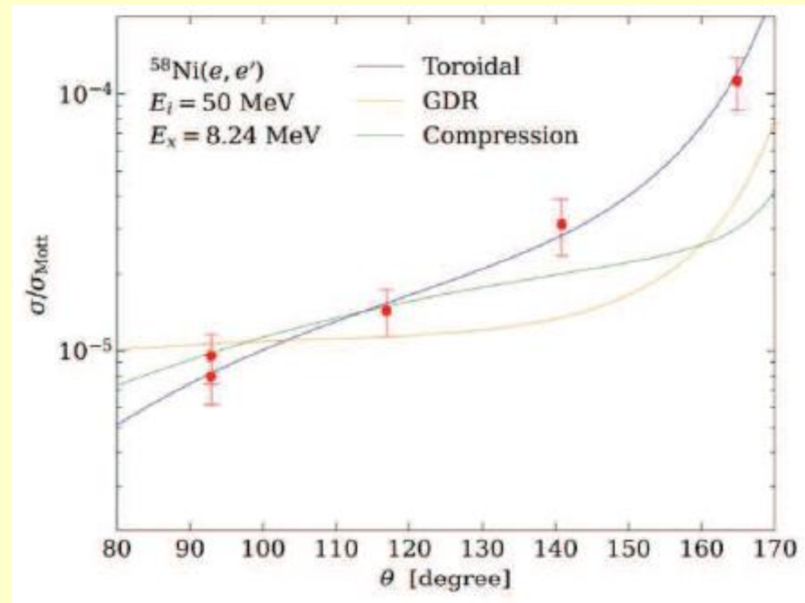




- **large E1 toroidal strength**
- **typical toroidal proton and neutron currents**







The calculations well describe Mettner's and Reitz's (e,e') data

Just toroidal states (not GDR or compression) describe the slope in Mettner's data

This is the first (e,e')-based indication of E1 toroidal states in nuclei.

Combined (e,e'), (p,p'), (γ,γ') analysis: P. von Neumann-Cosel, V.O. Nesterenko, I. Brandherm, P.I. Vishnevskiy, P.-G. Reinhard, J. Kvasil, H. Matsubara, A. Repko, A. Richter, M. Scheck and A. Tamii, arXiv: 2310.04736v1 [nucl-ex], submitted to Nature Communications.

Next our step: $(e,e'\gamma)$

C.N. Papanikolas et al, PRL 54, 26 (1985):
first measurement of the relative FL/FT sign in 12C

$$\frac{d^4\sigma}{d\Omega_\gamma d\Omega_e\, d\omega\, dE_\gamma} = \sigma_{\rm Mott}\left(\frac{\Gamma_{\gamma f}}{\Gamma}\right)\Big\{V_L U_L |F_L(q)|^2 + V_T U_T |F_T(q)|^2 + V_I U_I \cos\phi_\gamma F_L(q) F_T(q) + V_S U_S \cos 2\phi_\gamma F_T(q) F_T(q)\Big\},$$

longitudinal-transversal interference terms allow to measure the relative sign of FL and FT.

In the long-wave approximation, Siegert's theorem gives the negative sign:

$$F_T(q) = -\frac{\omega}{q}\left(\frac{\lambda+1}{\lambda}\right)^{1/2} F_L(q) \quad \text{for} \quad q \to \omega.$$

For transversal toroidal E1 states, we expect the opposite sign. This could be a signature of the toroidal mode.
Besides, Hill's vortex ring should polarize the outcoming gamma quant

New $(e,e'\gamma)$ facilities in TU Darmstadt

Inverse Compton scattering: instructive example

M. Scheck et al, **"Photoresponse of 60Ni below 10-MeV excitation energy: Evolution of dipole resonances in *f p*-shell nuclei near *N* = *Z*",** PRC **88**, 044304 (2013).

1) (γ,γ') measurements (Nuclear Resonance Fluorecence- NRF)using bremsstrahlung with a continuous photon-energy distribution (TU, Darmstadt)

- selective mainly for dipole states
- very large background, especially at low-excitation energy

2) $(\vec{\gamma},\gamma')$ measurements using 100% linearly polarized, Compton-backscattered laser photons with a quasimonochromatic energy distribution in the entrance channel (Duke Free Electron Laser Laboratory (DFELL) at the Triangle Univerity Durham, USA)

- to determine the parity of dipole states (E1 vs M1)

The use of two photon sources, produced via two different reaction mechanisms that complement each other, makes it possible to extract maximum information about the nuclear dipole response in a most efficient way.

To investigate nuclear vorticity in in Sarov/Novosibirsk facilities using various reactions:(e,e'),$(e,e'\gamma)$, (γ,γ'), $(\vec{\gamma},\gamma')$, …

Conclusions

★ TDR is a remarkable example of the vortical intrinsic electric nuclear flow.
TDR is the general feature of atomic nuclei,

★ Why this is interesting:
- dynamics beyond the continuity equation,
- crossover with toroidal dipoles in other quantum systems
(hydrodynamics of turbulent flow, metamaterials, HIC, neutron stars, …)

★ Individual toroidal states (ITS) in light nuclei as a new way to explore vortical excitations. Interplay of cluster and vortical modes.

★ First results: (e,e')-based prediction of ITS in 58Ni.

★ **Outlook:** DWBA calculations, search of ITS in $(e,e'\vec{\gamma})$ and NRF, usage of HIC procedures to identify toroidal structures, …

in collaboration with:

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P. Vishnevskiy,
BLTP JINR, Dubna; Inst. Nucl. Phys., Almaty, Kazakhstan

Thank you for attention!