Dipole toroidal resonance: vortical properties, relation to pygmy mode, deformation impact

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EuNCP2015, Groningen, 31.08-04.09.2015

Content:

- Exotic isoscalar E1 resonances:
  - toroidal (TR),
  - compressional (CR)
  - pygmy (PDR)

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

- TR: the most accurate measure of the nuclear vorticity

P.-G. Reinhard, V.O.N, A. Repko, and J. Kvasil,
PRC 89, 024321 (2014).

- TR: anomalous deformation splitting

J. Kvasil, V.O. Nesterenko, W. Kleinig, and P.-G. Reinhard,
Phys. Scr. 89, 054023 (2014).

- TR: origin of PDR

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

- TR: experimental status

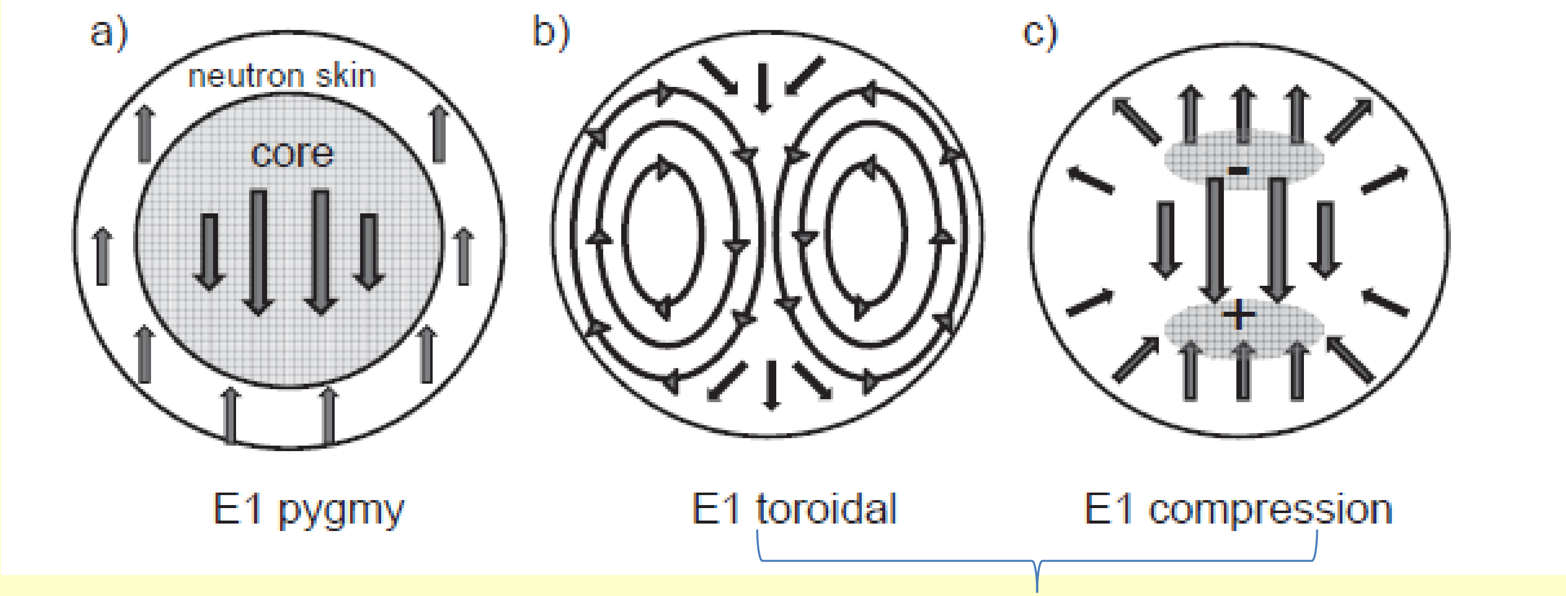
Exotic dipole resonances

[1] V.M. Dubovik and A.A. Cheshkov, Sov. J. Part. Nucl. v.5, 318 (1975).
[2] S.F. Semenko, Sov. J. Nucl. Phys. v. 34, 356 (1981).

R. Mohan et al (1971),

V.M. Dubovik (1975)
S.F. Semenko (1981)

M.N. Harakeh (1977)
S. Stringari (1982)



Dominate in E1(T=0) channel
(after exclusion of spurious E1(T=0) c.m. motion)

irrotational

vortical

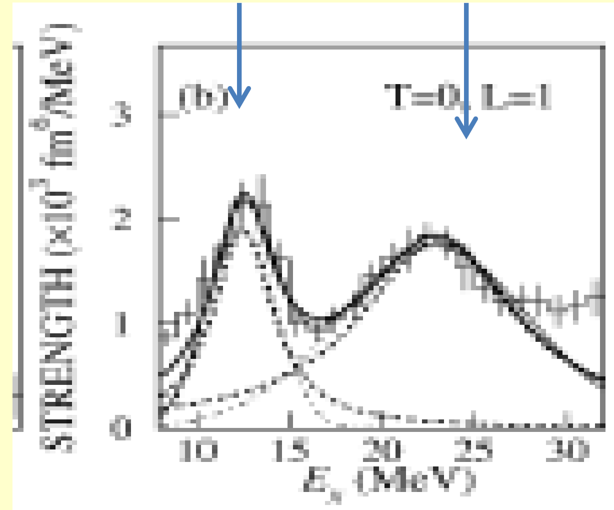
irrotational

TR and CR consitute low- and high-energy ISGDR branches

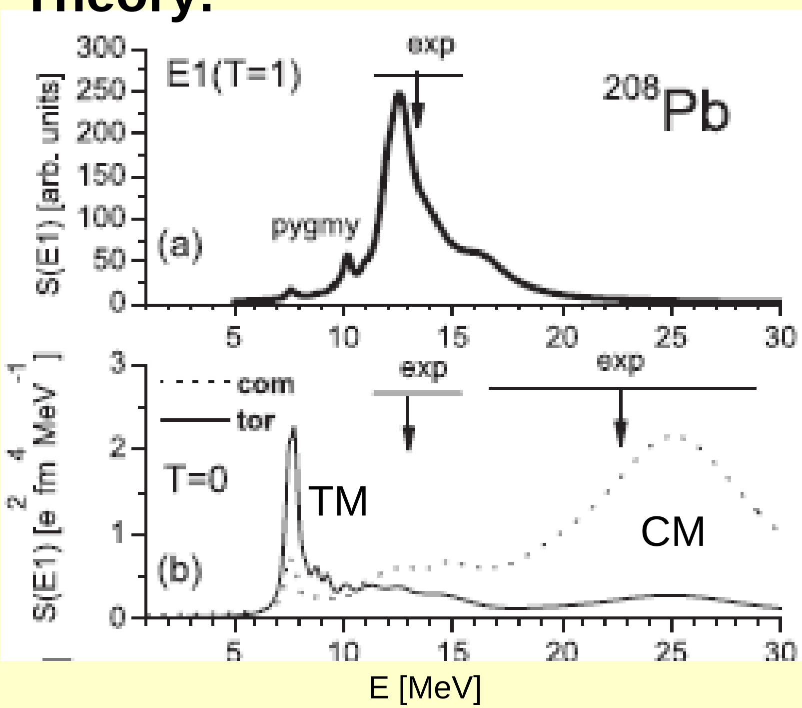
Experiment: (α, α')

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, PLB 557, 12 (2003),
PRC 69, 051301(R) (2004)

LE (toroidal) HE (compression)



Theory:



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

Skyrme RPA, SLy6

Toroidal E1 operator:

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

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

- second-order part of the electric operator

Compression E1 operator:

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

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

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

- **TR and CR are ideal examples of the vortical and irrotational motion**

- **to be used below a main test cases**

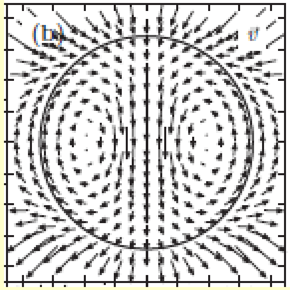
P.-G. Reinhard, V.O. N., A. Repko, and J. Kvasil,
"Nuclear vorticity in isoscalar E1 modes: Skyrme-RPA analysis",
Phys. Rev. C89, 024321 (2014).

Toroidal motion as the measure of the nuclear vorticity

Two familiar conceptions of nuclear vorticity : HD, RW

1. Hydrodynamical vorticity:

$$\vec{w}(\vec{r}) = \vec{\nabla} \times \vec{v}(\vec{r}) \qquad \delta\vec{v}(\vec{r}) = \frac{\delta \vec{j}_{nuc}(\vec{r})}{\rho_0(\vec{r})}$$



2. RW vorticity

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

$$\delta\vec{j}_{(fi)}(\vec{r}) = \left\langle j_f m_f \,|\, \hat{\vec{j}}_{nuc}(\vec{r}) \,|\, j_i m_i \right\rangle = \sum_{\lambda\mu} \frac{(j_i m_i \lambda\mu \,|\, j_f m_f)}{\sqrt{2j_f+1}} [j^{(fi)}_{\lambda\lambda-1}(r)\vec{Y}^{*}_{\lambda\lambda-1\mu} + j^{(fi)}_{\lambda\lambda+1}(r)\vec{Y}^{*}_{\lambda\lambda+1\mu}]$$

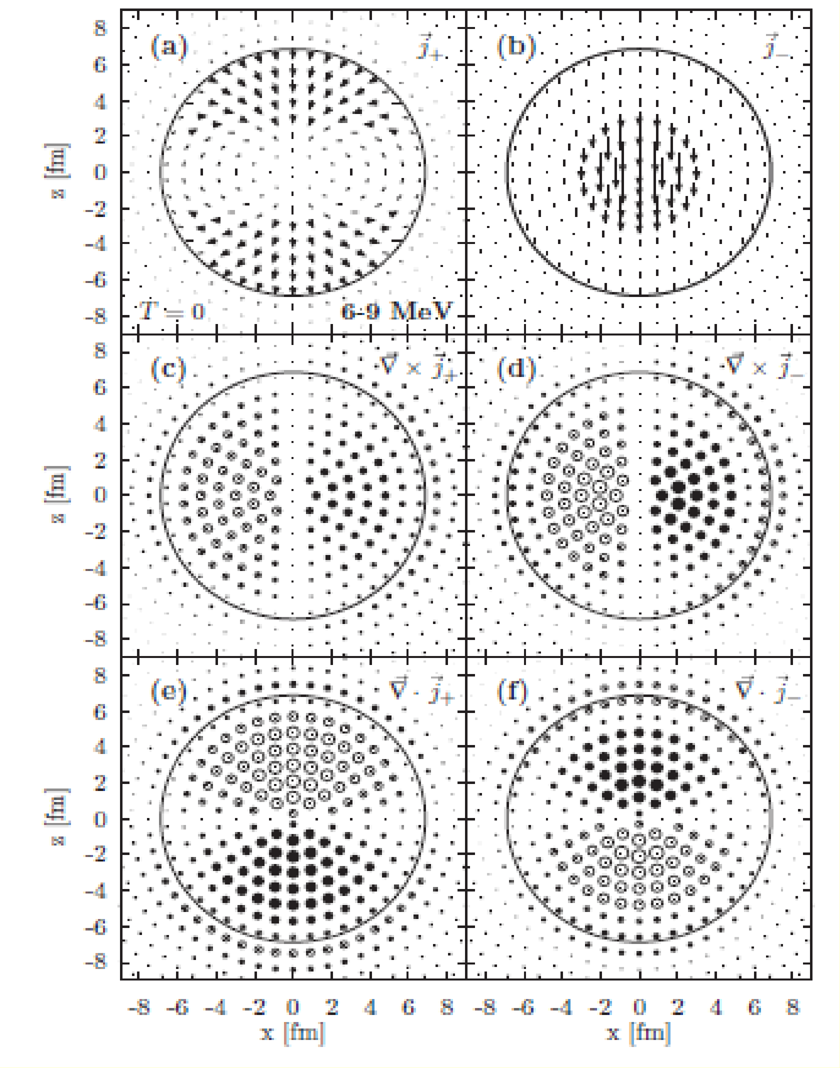
$$\delta\vec{j}^{\nu}_{1\mu}(\vec{r}) = \left\langle \nu \,|\, \hat{\vec{j}}_{nuc}(\vec{r}) \,|\, 0 \right\rangle = -\frac{i}{\sqrt{3}} [\underbrace{j^{\nu}_{10}(r)}_{j_-}\vec{Y}^{*}_{10\mu} + \underbrace{j^{\nu}_{12}(r)}_{j_+}\vec{Y}^{*}_{12\mu}]$$

- current transition density

$j^{\nu}_{+}(r)$ - independent part of charge-current distribution,
- decoupled from CE in the integral sense
- may be the measure of the vorticity

HD and j+ prescriptions give opposite conclusions on CM vorticity!

j+ j-



208Pb:
all RPA states
at E=6-9 MeV

j+, j-:
- both have strong curl's and div's
- there is no any advantage of j+ over j- to represent the vorticity

The vortical or irrotational character of the flow is provided not by j+ or j- components separately but by their proper superposition

$$\langle \nu / \hat{M}_{tor}(E1\mu) / 0 \rangle = -\frac{1}{6c}\int dr\, r^2 \left[\frac{\sqrt{2}}{5} r^2 j_+^{\nu}(r) + (r^2 - \langle r^2 \rangle_0) j_-^{\nu}(r)\right]$$

$$\langle \nu / \hat{M}_{com}(E1\mu) / 0 \rangle = -\frac{1}{6c}\int dr\, r^2 \left[\frac{2\sqrt{2}}{5} r^2 j_+^{\nu}(r) - (r^2 - \langle r^2 \rangle_0) j_-^{\nu}(r)\right]$$

Finally:

- RW conception of the vorticity is not relevant:

- **- CE-unrestricted in integral sense,**
- **- failure for CM,**
- **- j+ has no advantages over j-.**

-TR conception is more correct:

- **- vortical by construction,**
- **- locally CE-unrestricted,**
- **- close to HD conception,**
- **- gives visually vortical image,**
- **- correct for both TR and CR.**

So just the toroidal current and strength are the best measure of the nuclear vorticity .

Deformation effects
in the toroidal resonance

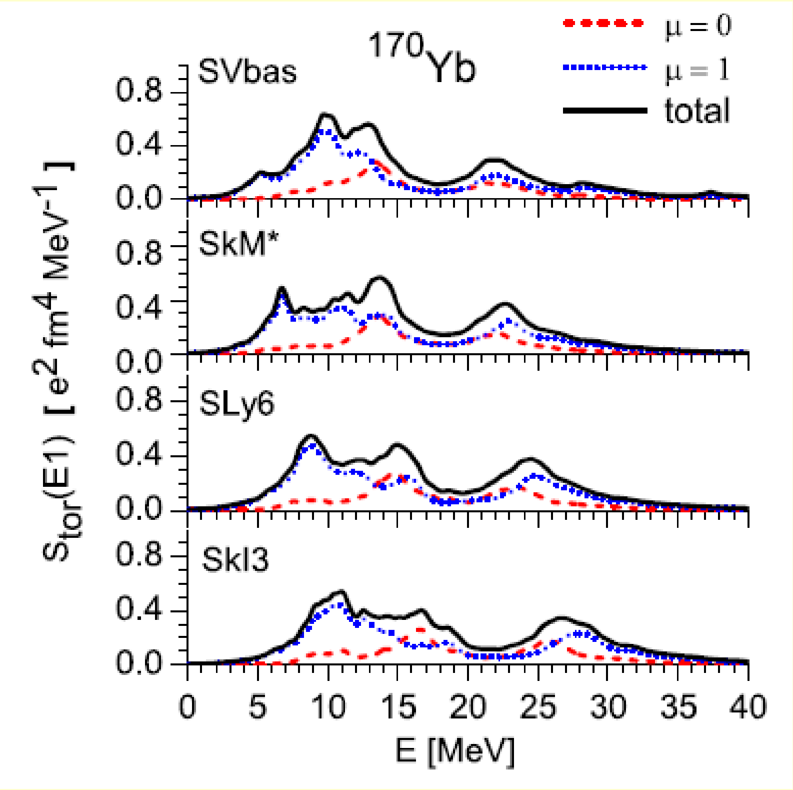
J. Kvasil, V.O. Nesterenko, W. Kleinig, D. Bozik, P.-G. Reinhard, and N. Lo Iudice,
"Toroidal, compression, and vortical dipole strengths in {144-154}Sm: Skyrme-RPA exploration of deformation effect",
Eur. Phys. J. A, v.49, 119 (2013).

J. Kvasil, V.O. Nesterenko, W. Kleinig, and P.-G. Reinhard,
"Deformation effects in toroidal and compression dipole excitations of 170Yb: Skyrme-RPA analysis",
Phys. Scri., v.89, n.5, 054023 (2014).

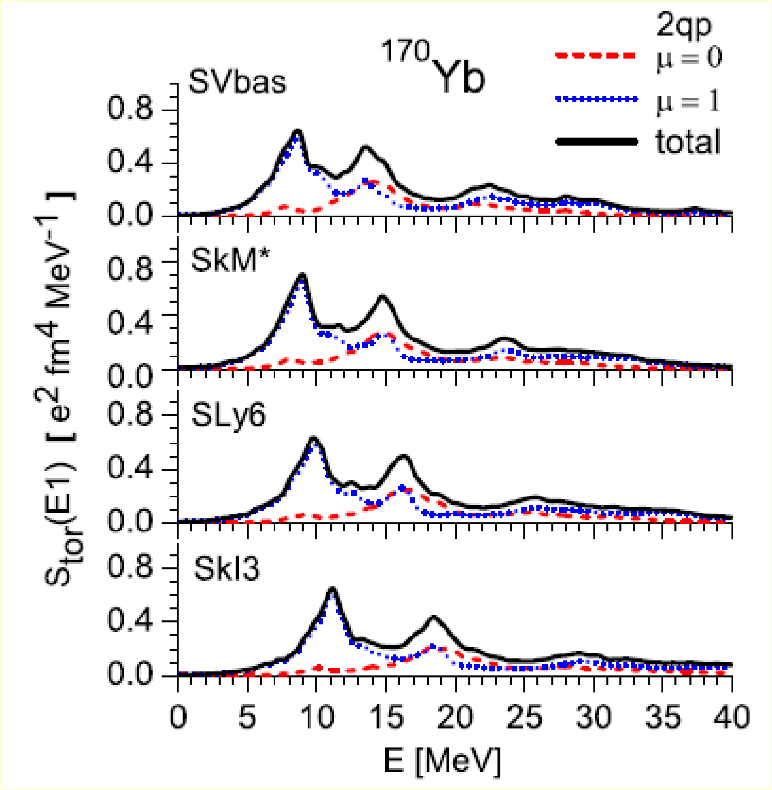
Deformation effects in the toroidal mode

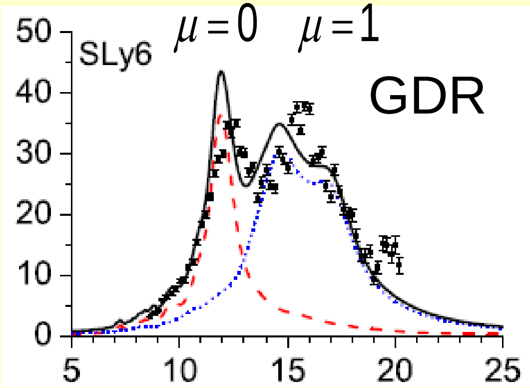
J. Kvasil, VON, W. Kleinig and P.-G. Reinhard, Phys. Scr. 89, 054023 (2014)

RPA



2qp





GDR: $E(\mu=0) < E(\mu=1)$

TM: $E(\mu=0) > E(\mu=1)$

Unusual sequence of $\mu=0$ and $\mu=1$ branches

Deformation (not resid. Interaction) effect

Non-Tassie mode!

$$\nabla \times \vec{F} = 0, \nabla \cdot \vec{F} = 0$$

$$\vec{F} = \nabla\Phi, \Phi = r^{\lambda} Y_{\lambda\mu}$$

Relation of E1 toroidal and pygmy resonances

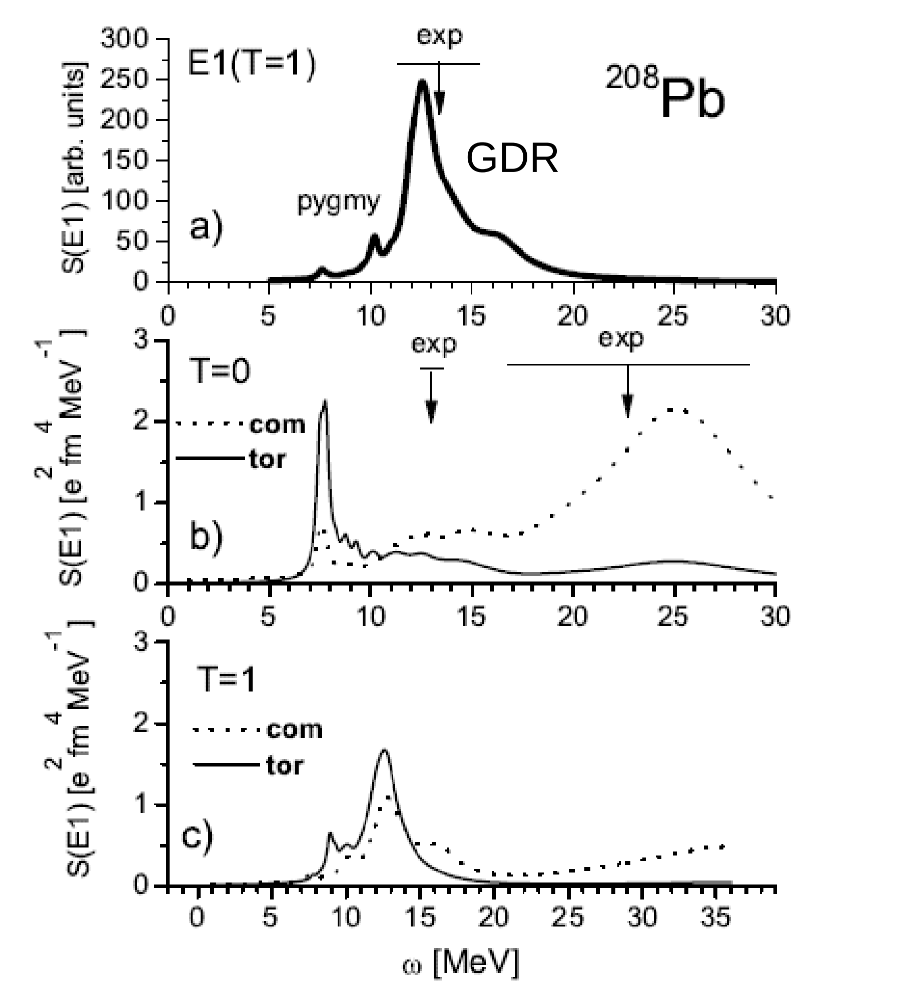
A. Repko, P.-G. Reinhard, V.O. Nesterenko, and J. Kvasil,
"Toroidal nature of the low-energy E1 mode",
Phys. Rev. C87, 024305 (2013).

V.O. Nesterenko, A. Repko, P.-G. Reinhard, and J. Kvasil,
"Relation of E1 pygmy and toroidal resonances",
EPJ Web of Conferences, 93, 01020 (2015); arXiv:1410.5634[nucl-th],

Review:
D. Savran, T. Aumann, and A. Zilges,
“Experimental studies of the Pygmy Dipole Resonance”
Prog. Part. Nucl. Phys. 70, 210 (2013).

Strength functions SLy6

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

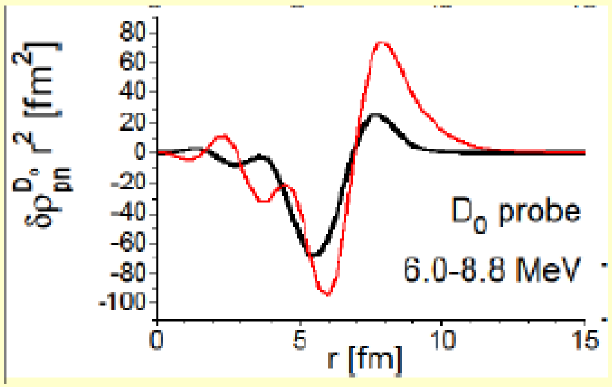


Two peaks at 7.5 and 10.3 MeV in agreement to RMF calculations
(D. Vretenar, N. Paar, P. Ring, PRC**, 63**, 047301 (2001))

(α,α') experiment of Uchida et al (2003)

PDR region hosts TR and CR!

Typical PDR transition density:

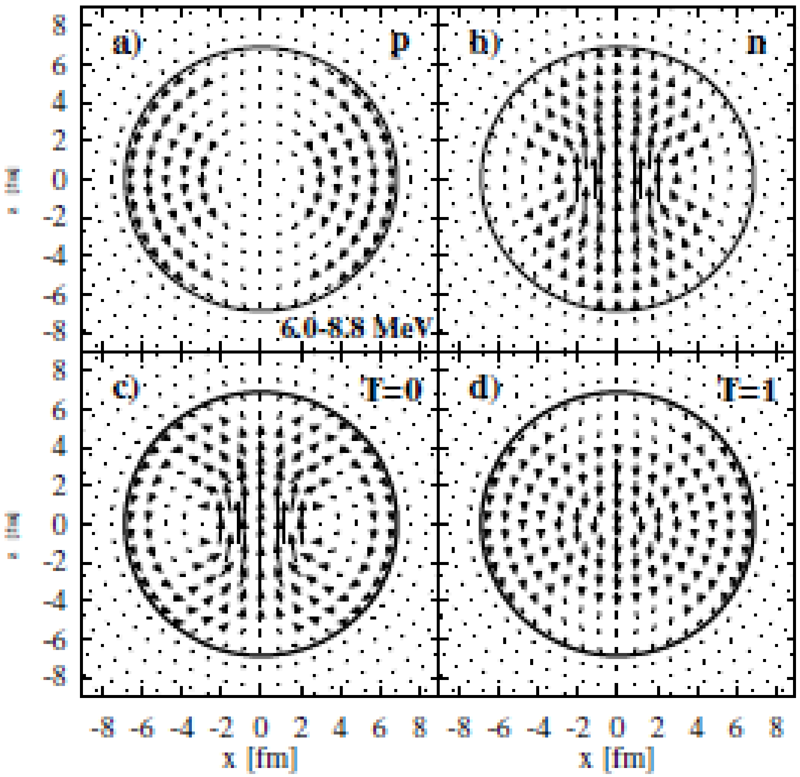


- n
- p

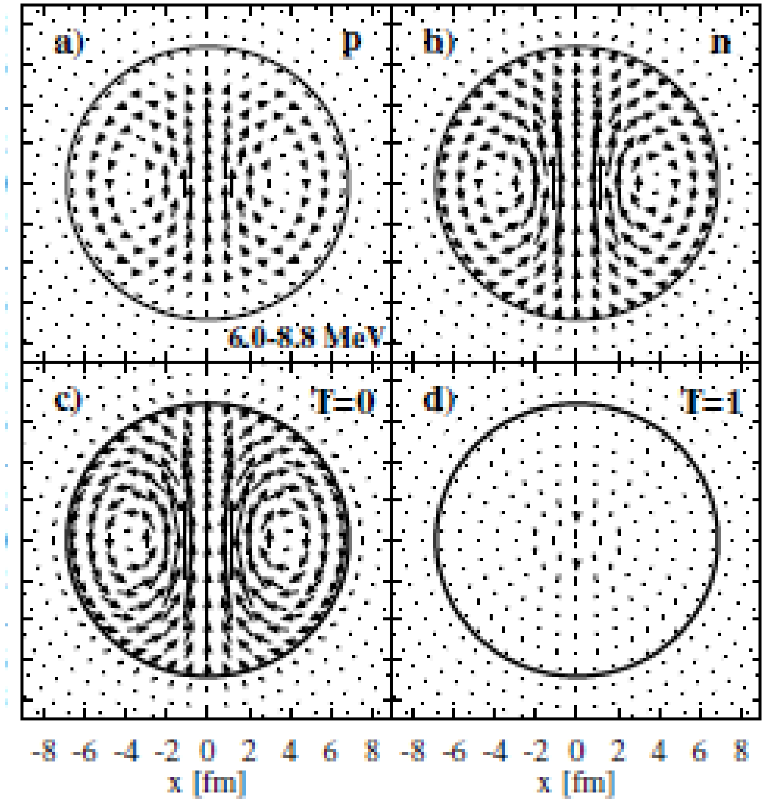
RPA vs 1ph

V.O.N., A. Repko, P.-G. Reinhard, and J. Kvasil, EPJ Web of Conferences, 93, 01020 (2015);

1ph



RPA

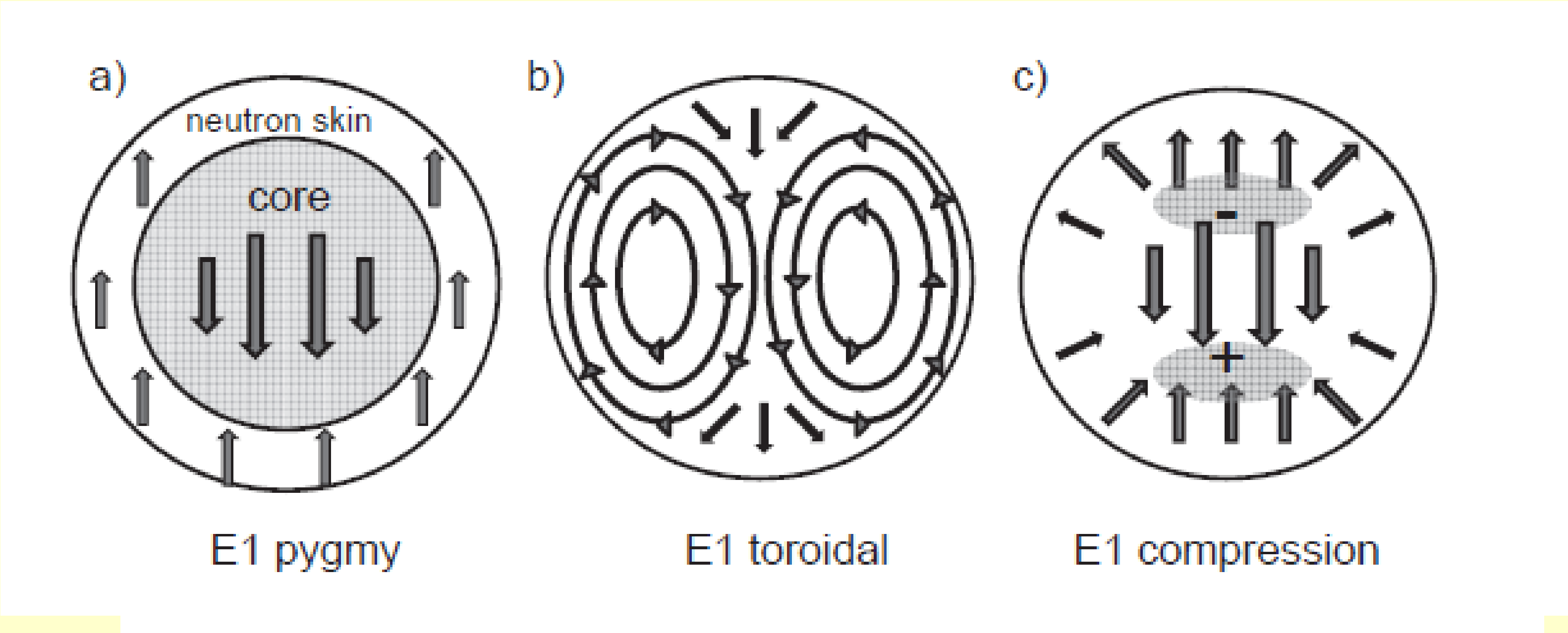


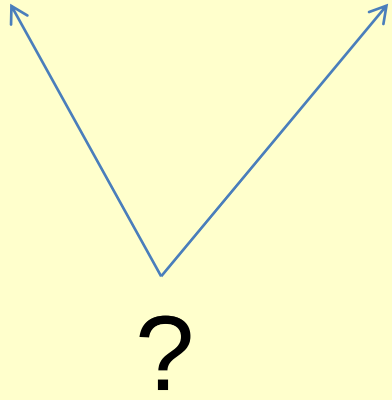
-both isoscalar and isovector
- toroidal flow mainly fom neutrons

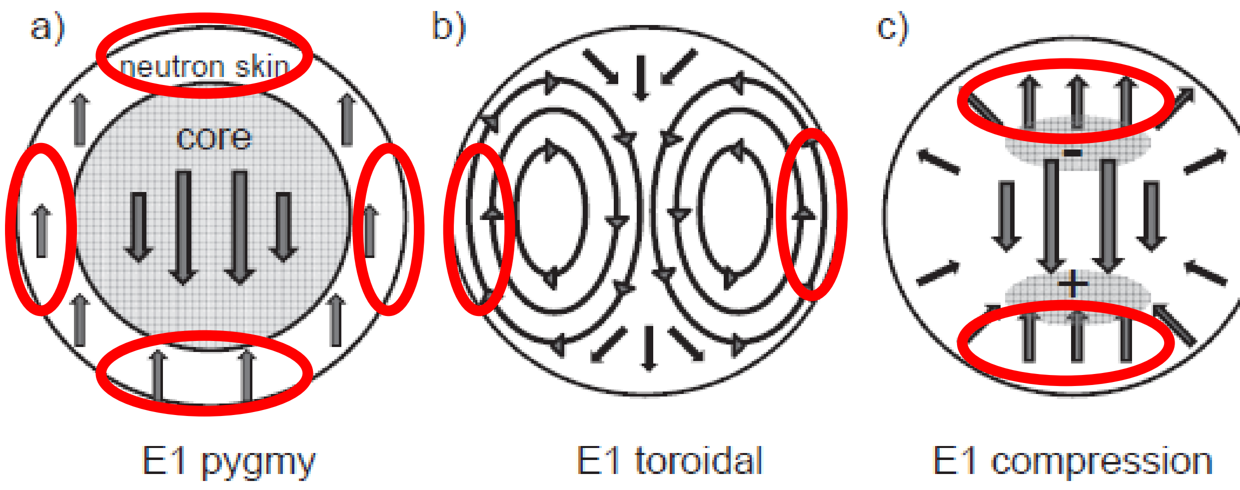
- mainly isoscalar
- toroidal flow from both n/p

So the toroidal flow is basically formed already by the mean-field.
But residual interaction makes it collective and more impressive.

Does the vortical toroidal flow contradicts the irrotational PRD picture?





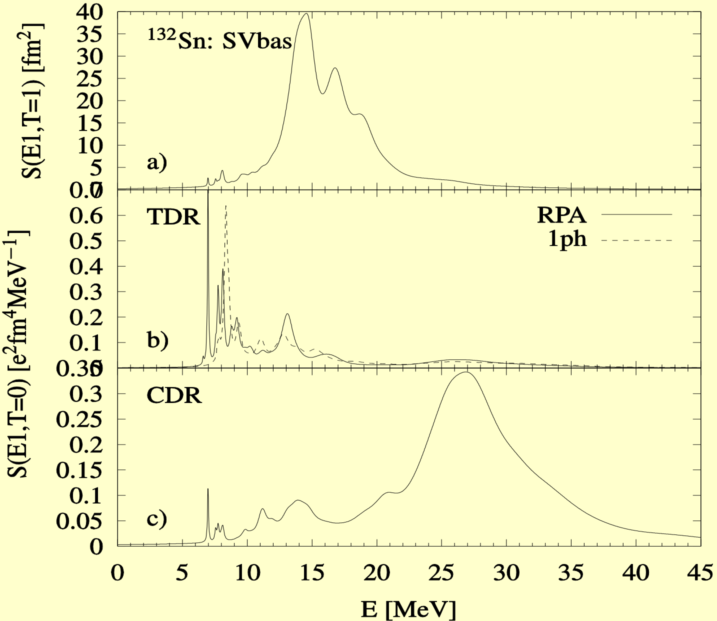


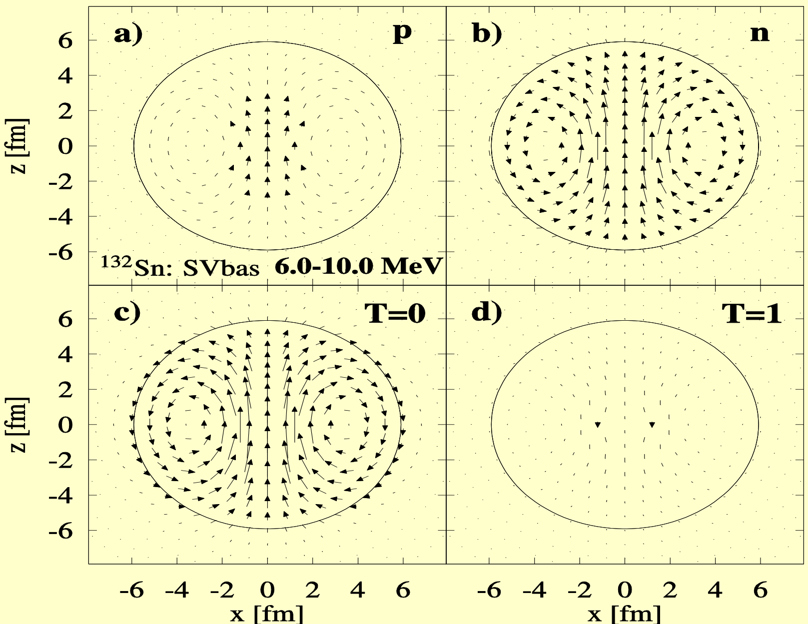
V.O. Nesterenko, A. Repko, P.-G. Reinhard, and J. Kvasil, "Relation of E1 pygmy and toroidal resonances", arXiv:1410.5634[nucl-th],

- PDR can be viewed as a local peripheral part of TR and CR

- Our calculations demonstrate the TR flow in PDR energy region also in Ni, Zr, Sn, …

132Sn, SVbas, with PDR



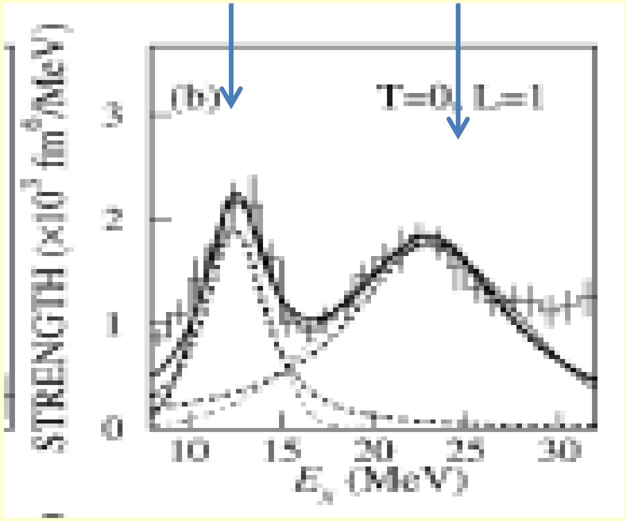


TR: experimental status

Experiment: (α,α')

M.Uchida et al, PLB 557, 12 (2003),
PRC 69, 051301(R) (2004)

LE (toroidal) HE (compression)



Looks reasonable since the theory predicts only TR to form the low-energy part of ISGDR.

Anyway is it possible to propose a reaction where TR:
- could be observed alone or
- could demonstrate a particular fingerprint?

The reaction should be:
- IS (to suppress the effect of the dominant E1(T=1) modes)
- transversal but not polluted by magnetic form-factors
- sensitive to nuclear interior

(e,e'), - both IS/IV, strong magnetic forf-mactor
(α,α') - peripheral, not sensitive to nuclear interior,
(p,p') - both IS/IV

} not good

Reactions with polarized beams/targets?

So far (α,α') is the best option where TR can be excited:
- not directly but through the coupling with CR or PDR
- through peripheral part of TR

Conclusions

★ **Toroidal current (strength) is the most relevant fingerprint and measure of the nuclear vorticity.**
- It is more convenient and relevant than RW and HD prescriptions.
- TR is the only known example of the vortical collective electric motion.

★ **Anomalous deformation splitting in TR**

★ **PDR seems to be a local surface part of the toroidal motion.**

PDR is a complex mixture of:

- **IS/IV,**
- **collective/s-p,**
- **irrotational/vortical,**
- **TM / CM / GDR,**
- **complex configurations**

But the vortical TM seems to dominate!

★ **Unambiguous experimental observation of TR: still a challenge.**
(α,α') **is so far best.**

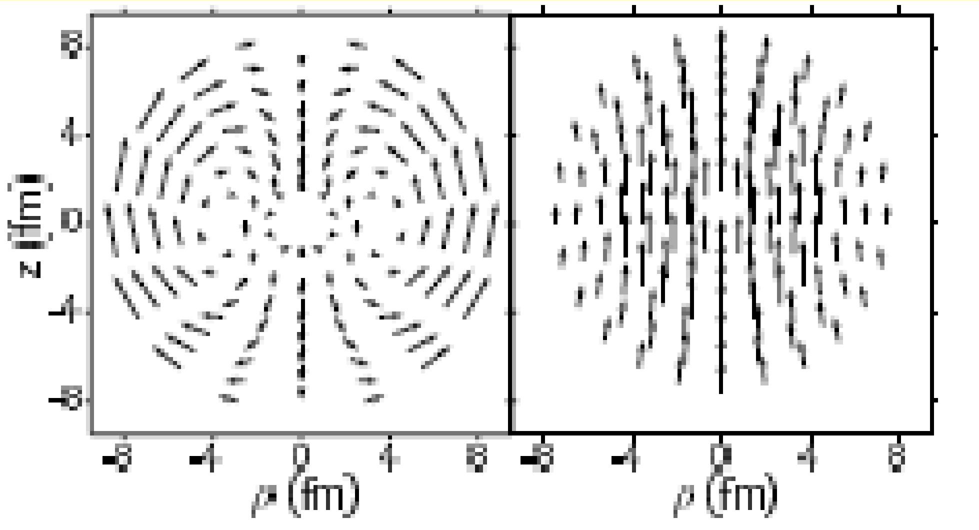
Thank you for attention!

N.Ryezayeva et al, PRL 89, 272502 (2002).

QPM calculations taking into account complex configurations

Summed QPM velocity fields in 6.5-10.5 MeV region

PDR GDR



Toroidal-like picture in T=1 channel .

$$\delta\vec{v} = \frac{N}{A}\delta\vec{v}_p - \frac{Z}{A}\delta\vec{v}_n$$

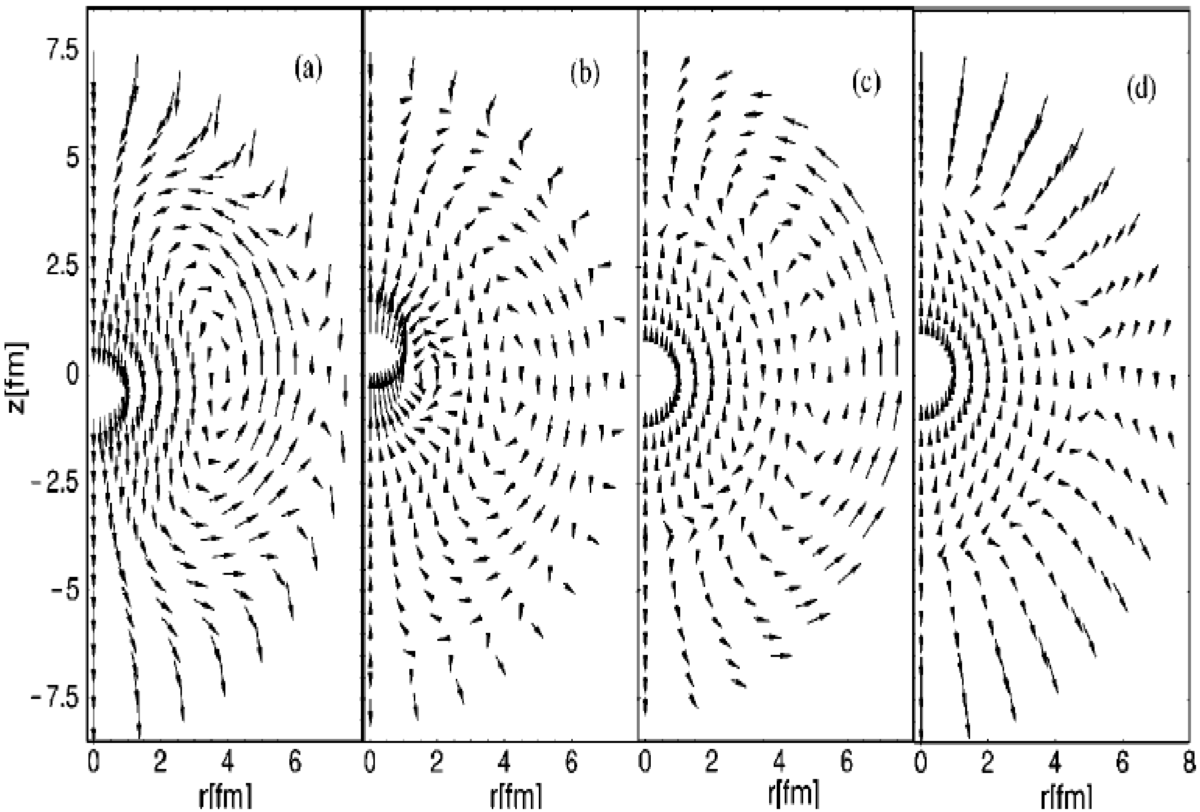
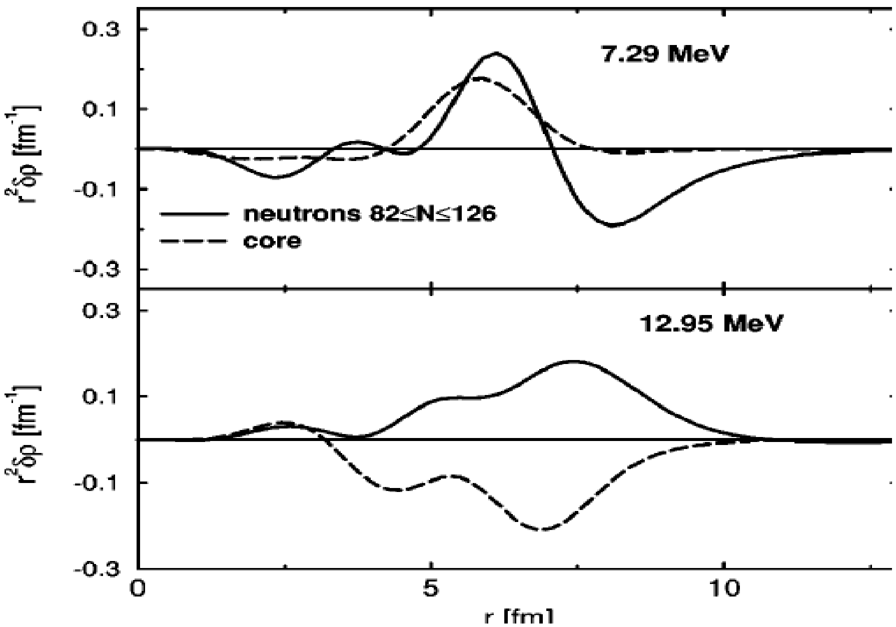


FIG. 3. Velocity distributions for the most pronounced dipole peaks in ^{116}Sn (see Fig. 2). The velocity fields correspond to the peaks at 8.82 MeV (a), 10.47 MeV (b), 17.11 MeV (c), and 30.97 MeV (d).

Motivation of PDR picture (2): oscillations of excess neutrons against the N=Z core

D. Vretenar, N. Paar, and P. Ring,
PRC, 63, 047301 (2001)

RMF calculations



RPA state at 7.29 MeV

neutron excess $82 \leq N \leq 126$

nuclear core