Isoscalar dipole excitations in N=Z nuclei

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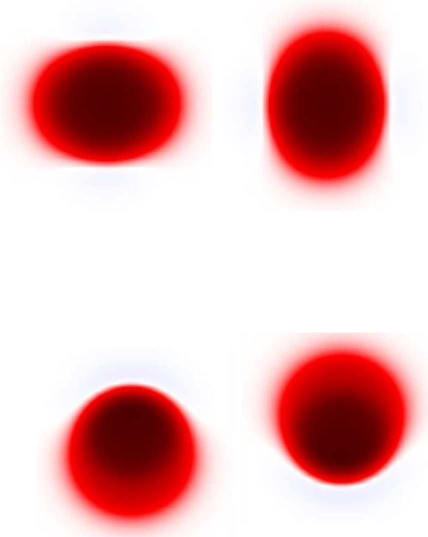
IBS Center for Exotic Nuclear Studies, August 12, 2020

And discussion based on RISP internal studies and reports [PP2017,PP&YHS2019]

Overview

- Prelude: Low-energy nuclear collective excitations
  - Vibrations (shape oscillations), rotations
  - Deformation, shell structure, clustering, reactions
- On the isoscalar, low-energy dipole (IS-LED) vibration
  - The misfit
- Gaps to fill in nuclear data - N=Z nuclei
- Summary



Prelude

Low-energy nuclear collective excitations

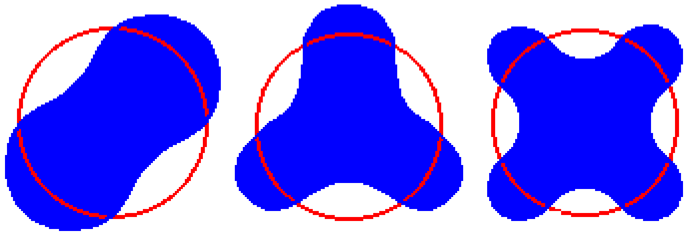
- Collective model: Vibrations and rotations
- Clustering: Molecule-like vibration+rotation
- *What else?*

Collective model: Vibrations and rotations

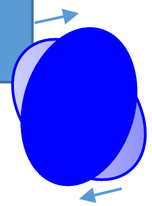
- Nuclei are characterized by collective behavior
- Collectivity is inferred from the electromagnetic transition strength to the ground state
  - cf “single-particle units”, or “Weisskopf units” (W.u.); or % of total EWSR
- **Collective model**: Nuclei as incompressible droplets of nuclear matter with only shape degrees of freedom
  - Deformed equilibrium shape: The nucleus can **rotate**
  - Shape oscillations: **vibrational** modes

Esp. middle of doubly-open shells

Esp. doubly- and singly-closed shell spherical nuclei



NJC Spooner

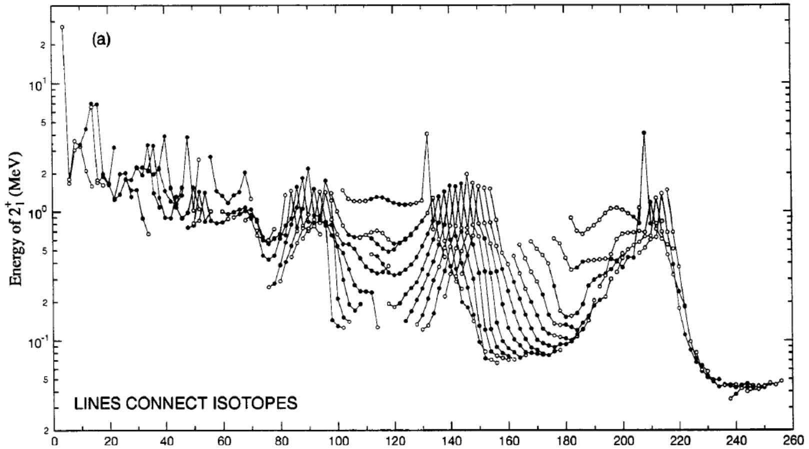


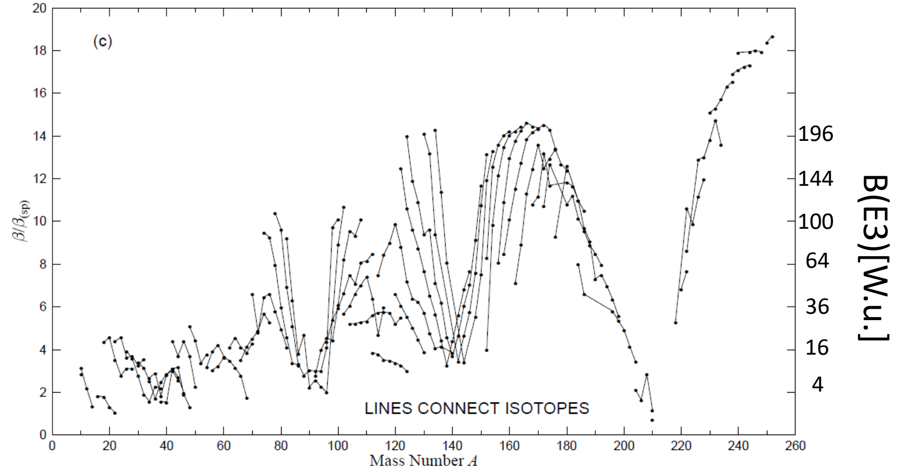
See, e.g., Rowe&Wood, “Fundamentals of Nuclear Models” vol.I, World Scientific 2010

Collective transitions - examples

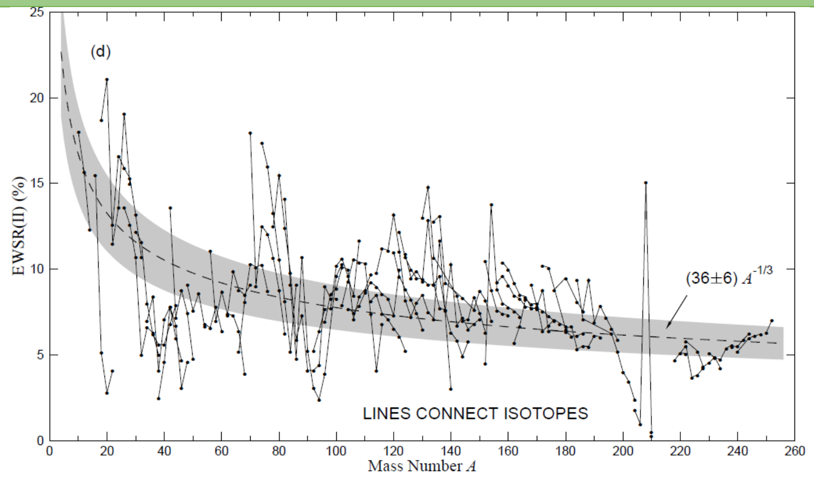
- Electric quadrupole, B(E2), from the 1^{st} 2^{+} to the ground state

Atomic Data and Nuclear Data Tables **78**, 1–128 (2001)





Clearly collective in most cases:
Transition strength >> 1W.u.
EWSR: >5%



$\beta = (4\pi/3ZR_0^2)[B(E2)\uparrow/e^2]^{1/2}$

$B(E2)\uparrow_{(sp)} = 2.97 \times 10^{-5} A^{4/3}\ e^2b^2$

Collective transitions - examples

- Electric octupole, B(E3), from the 1st 3^{-} to the ground state

Atomic Data and Nuclear Data Tables **80**, 35–82 (2002)

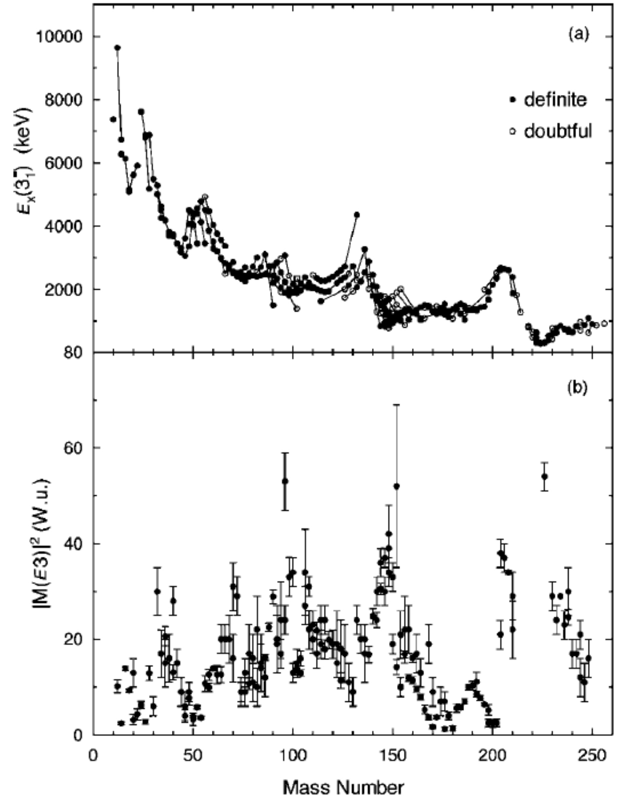


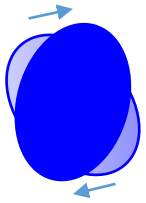
FIG. 1. (a) Excitation energy, $E_x(3_1^-)$, of the first 3$^-$ state in even–even nuclides as a function of mass number A (Table I). The open circles correspond to doubtful assignments. The lines connect isotopes. (b) Single particle strength, $|M(E3)|^2$, as a function of mass number A for $0_1^+ \to 3_1^-$ transitions (column 6 of Table VII).

Clearly collective in most cases: Transition strength >> 1W.u.

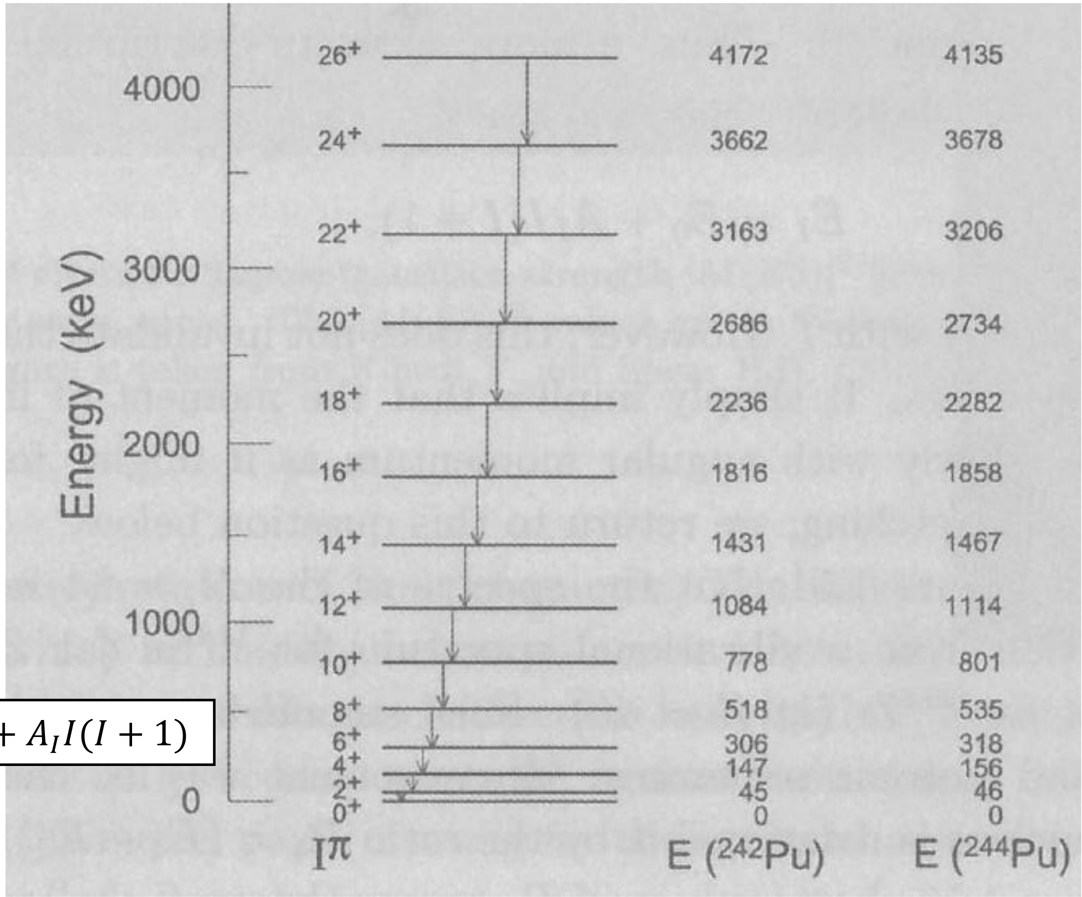
$$|M(E3)|^2 = 2.404 \times 10^6 \, B(E3)\uparrow / A^2 \text{ W.u.}$$

where $B(E3)\uparrow$ is in units of e^{2}b^3 (Ref. [17]). This expression is based on the assumption that $r_0 = 1.20$ fm.

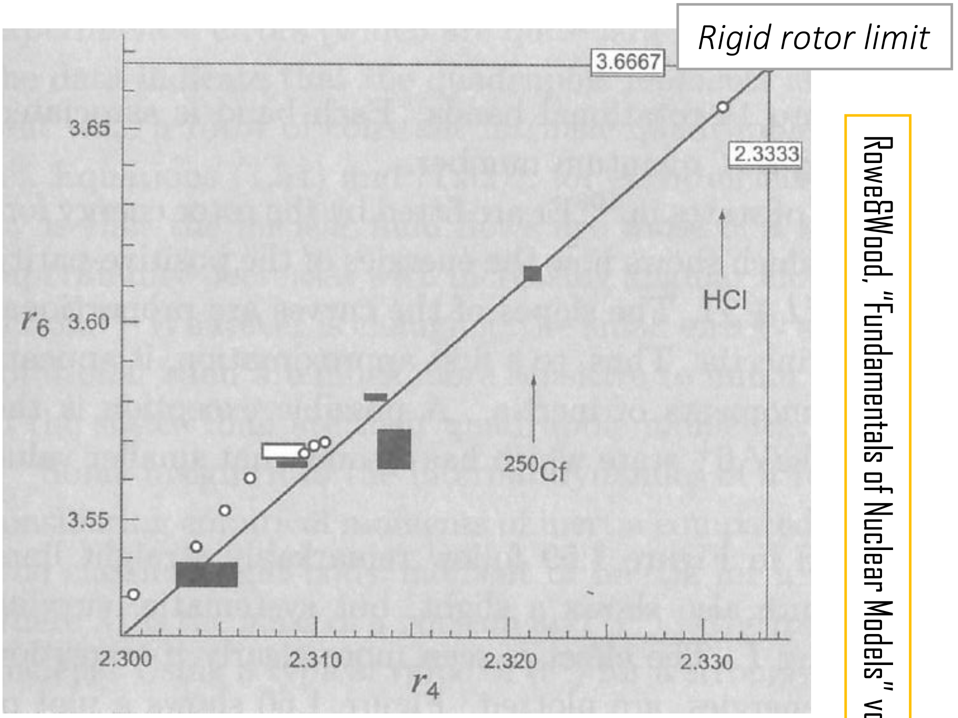
Rotational bands



- Examples:



$$E_I = E_0 + A_I I(I+1)$$



r_4 vs. r_6 for some the most rotational nuclei incl. Cf, Cm, Pu, Dy, Yb, Er, Hf isotopes

$$r_n \equiv \frac{E_n - E_{n-2}}{E_2 - E_0}$$

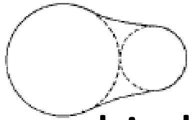
Rowe&Wood, "Fundamentals of Nuclear Models" vol.I, World Scientific 2010

Clustering: Vibrations and rotations

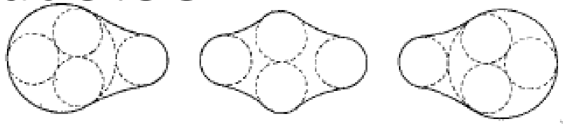
Light A=4n nuclei demonstrate alpha clustering(*)

Example

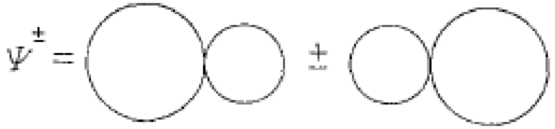
- First 0^+ of ^{16}O can be described by 4-body correlations (4p4h)

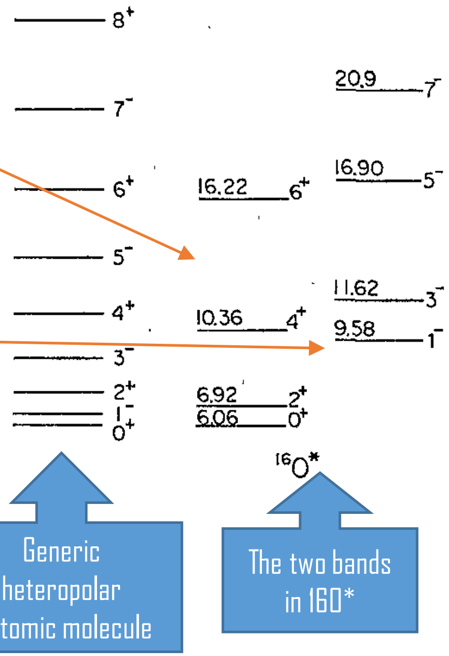


  - An even-parity rotational band is built on it
- Alpha-oscillation 1- state at 9.58



  - An odd-parity band is built on it



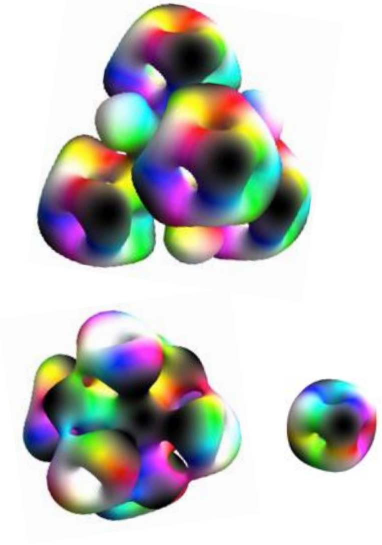


HoriuchiIkeda, Prog.Theor.Phys. 40(1968)277

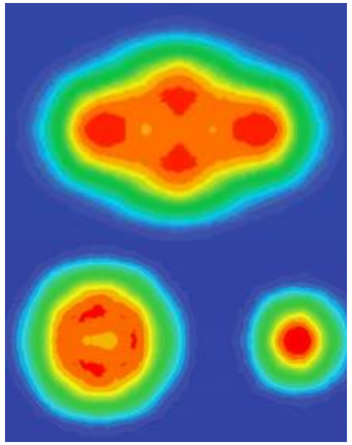
(*)For heavy nuclei see, e.g., Spieker+,PRL114(2015)192504

Recent approaches

Skyrmions
vs
α-Clusters



N.Manton

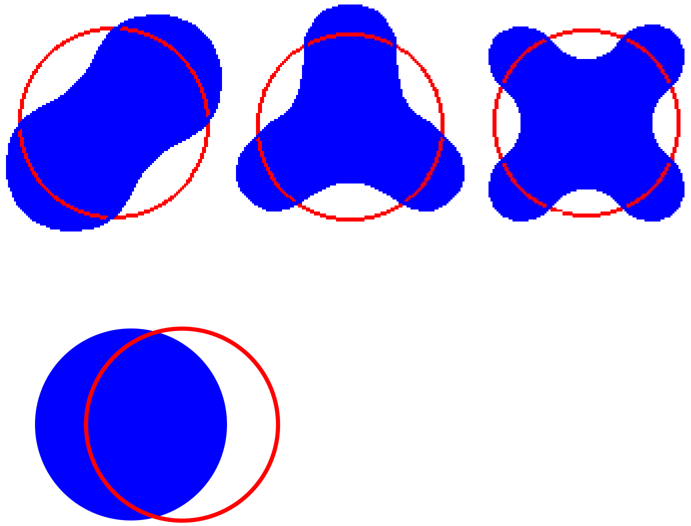


T.Nakatsukasa

Edme Mariotte
(Newton's cradle)

Museo Galileo

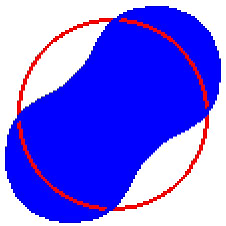
As shown at APCTP-TRIUMF Workshop, Pohang, Sept. 2018



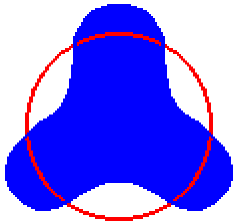
Low-energy dipole vibration?
The misfit

The misfit: Low-energy dipole vibration

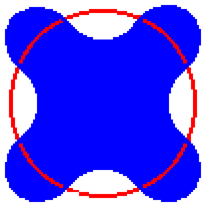
- Dipole vibrations cannot be described by the collective model:



Quadrupole
$r^2 Y_{2\mu}(\hat{r})$

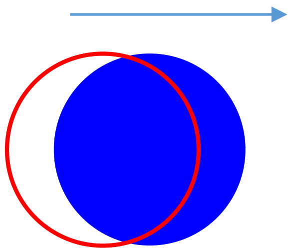


Octupole
$r^3 Y_{3\mu}(\hat{r})$



Hexadecapole
$r^4 Y_{4\mu}(\hat{r})$

The isoscalar dipole operator induces a displacement of the whole nucleus, not an excitation



Dipole
$rY_{1\mu}(\hat{r})$

Next in order: $r^3 Y_{1\mu}(\hat{r})$ can produce intrinsic dipole excitations

The misfit: Low-energy dipole vibration

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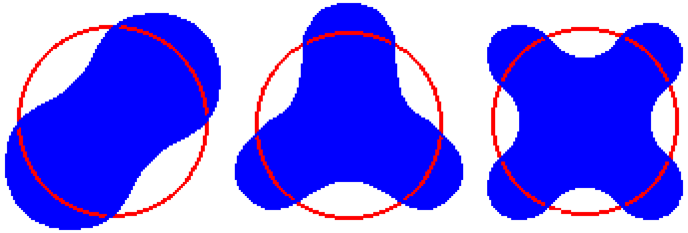
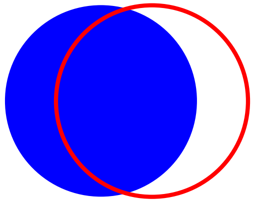


The electric dipole operator induces a displacement of the whole nucleus, not an excitation



- *But not shape oscillations:*
  - ❖ *Eg., some degree of compression*

The misfit: Low-energy dipole vibration

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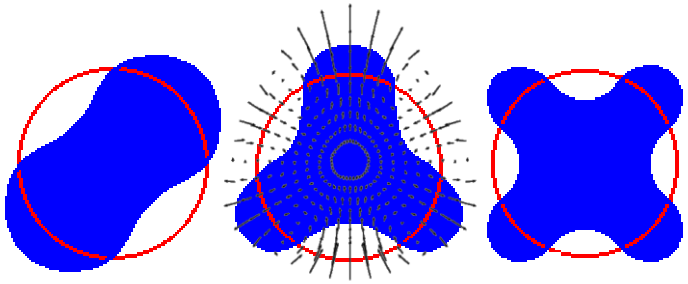

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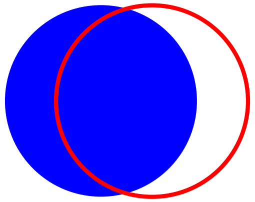

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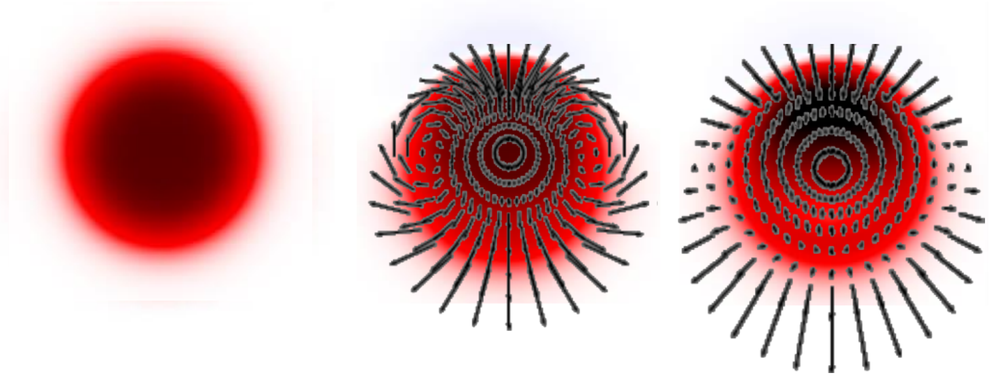


Cf. PP et al., EPJA47(2011)14, PRC89(2014)034306

Isoscalar, isovector, electric (EL) transitions

- Isoscalar transition operator:

$$O(IS;L) \propto \sum_{p=1}^{Z} f_L(r_p) Y_L(\hat{r}_p) + \sum_{n=1}^{N} f_L(r_n) Y_L(\hat{r}_n) = \sum_{i=1}^{A} f_L(r_i) Y_L(\hat{r}_i)$$

- Isovector transition operator:

$$O(IV;L) \propto \sum_{p=1}^{Z} f_L(r_p) Y_L(\hat{r}_p) - \sum_{n=1}^{N} f_L(r_n) Y_L(\hat{r}_n)$$

- Electric transition operator:

$$O(EL;L) \propto \sum_{p=1}^{Z} f_L(r_p) Y_L(\hat{r}_p) \propto \frac{1}{2}[O(IS;L) + O(IV;L)]$$

❖ ***Long-wavelength limit:*** $f_L(r) = r^L$

Electric vs isoscalar strength: L>1

- Electric multipole transition (long-wavelength limit):

$$\langle 0| \sum_{i=1}^{Z} r_i^L Y_L(\hat{r}_i) \, |f\rangle$$

- Isoscalar:

$$\langle 0| \sum_{i=1}^{A} r_i^L Y_L(\hat{r}_i) \, |f\rangle$$

- For N≈Z, (*proton density distribution*) ≈ ½ x (*total density distribution*) ⇒

$$B(EL) \approx \frac{1}{4} B(IS;L)$$

$$E_x B(EL)/EWSR(EL) \approx E_x B(IS;L)/EWSR(IS;L)$$

- Therefore (esp. for N ≈ Z), **strong B(EL) ↔ strong B(IS;L)** (similar information)

Electric vs isoscalar strength: L=1

- Electric dipole operator (long-wavelength limit):

$$\langle 0| \sum_{i=1}^{Z} r_i Y_1(\hat{r}_i) \,|f\rangle$$

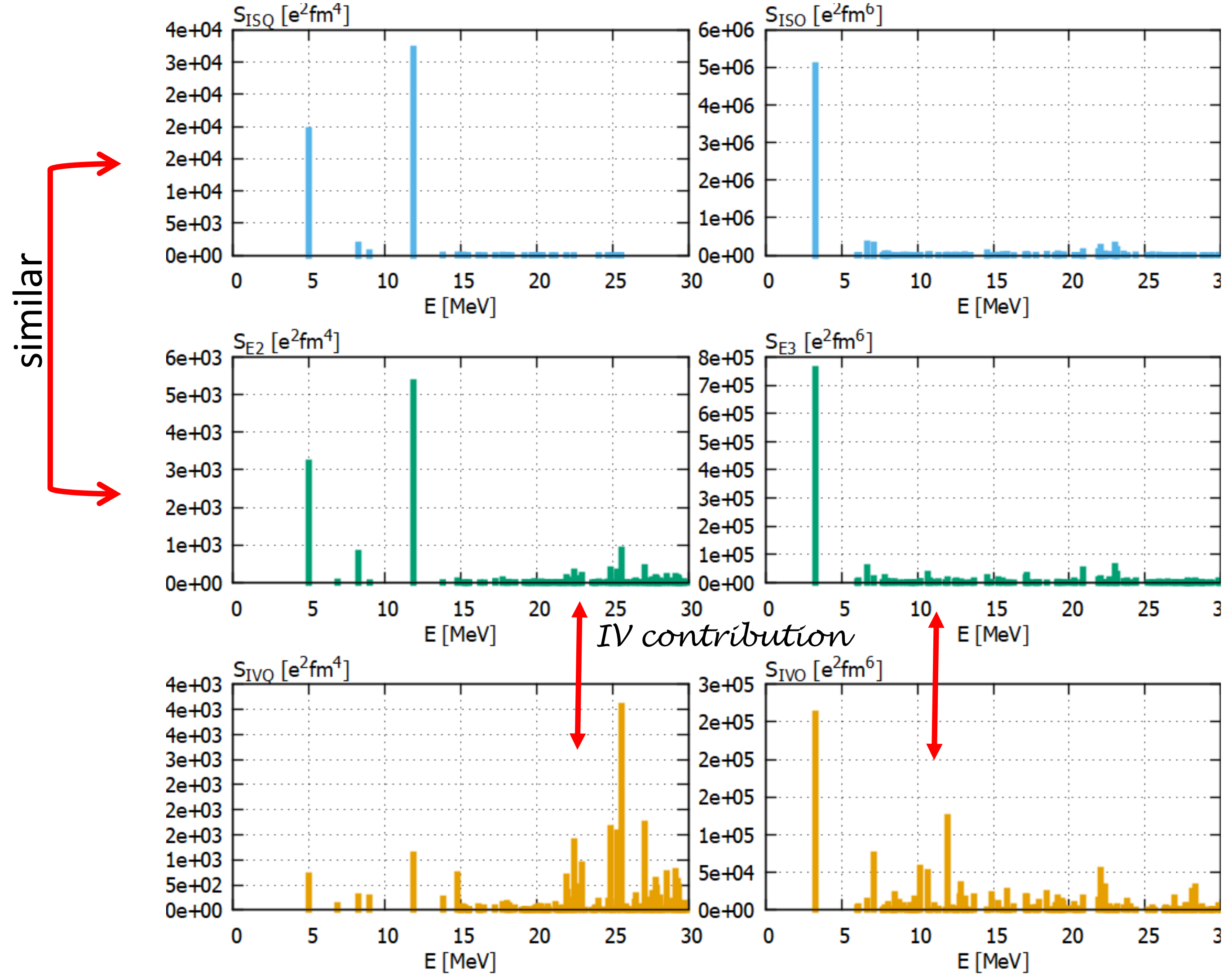
- The matrix element of $\langle 0| \sum_{i=1}^{A} r_i Y_1(\hat{r}_i) \,|f\rangle \propto \langle 0|Z_{CM}|f\rangle$ vanishes! (Translational invariance)
- Isoscalar operator: Next order needed for intrinsic excitations

$$\langle 0| \sum_{i=1}^{A} r_i^3 Y_1(\hat{r}_i) \,|f\rangle$$

$$O(EL;L) \propto \sum_{p=1}^{Z} f_L(r_p) Y_L(\hat{r}_p) \propto \frac{1}{2}[O(\cancel{IS};L) + O(IV;L)]$$

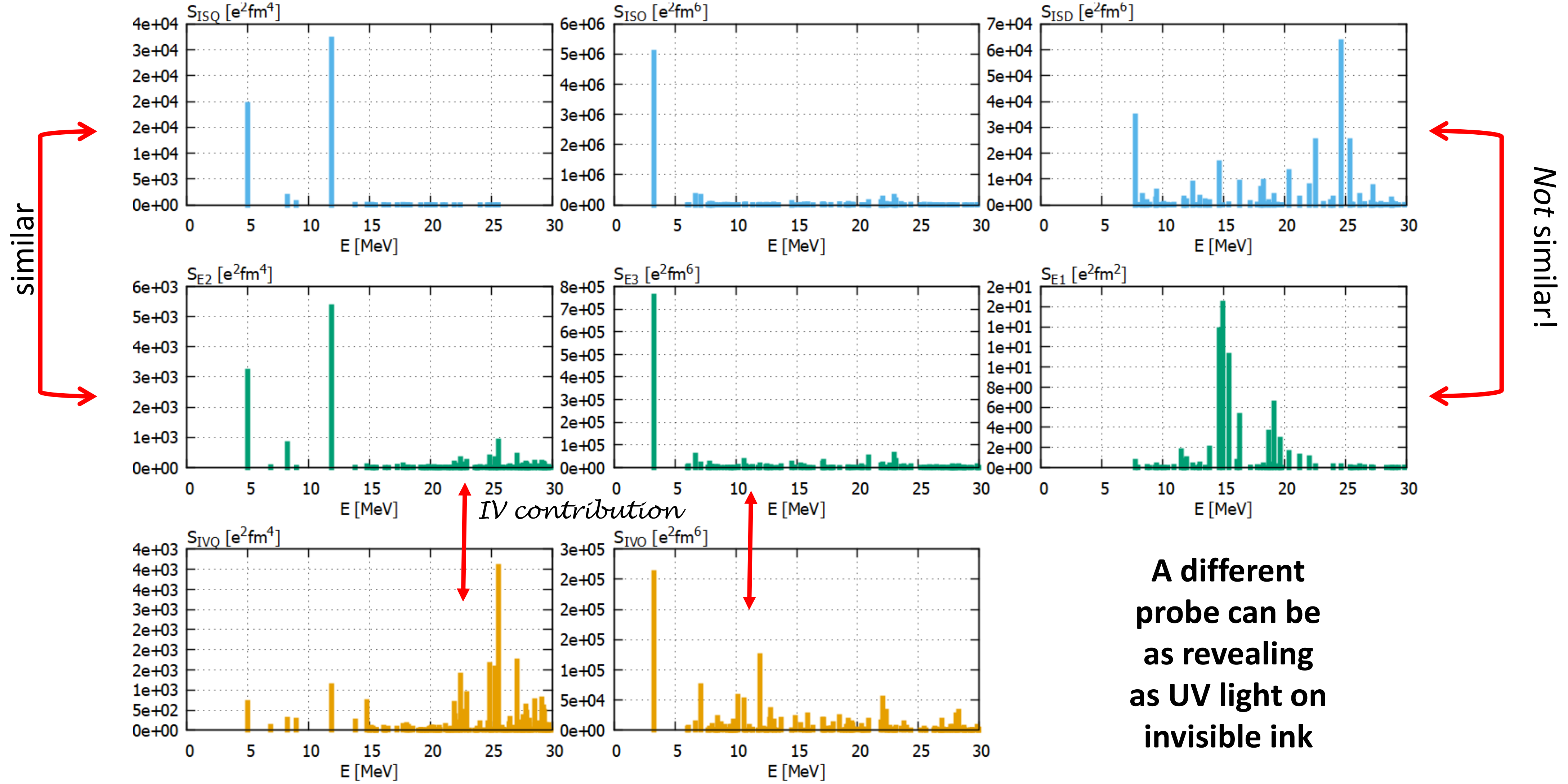
strong B(EL) $\not\Leftrightarrow$ strong B(IS;L)

Example: Electric response of ^{208}Pb



HF-RPA calculations with Gogny D1S interaction [PP]

Example: Electric response of ^{208}Pb



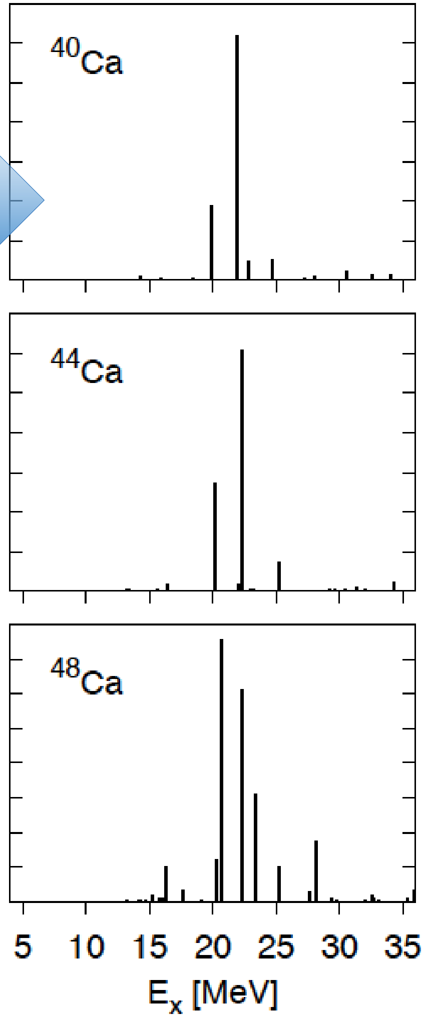
A different probe can be as revealing as UV light on invisible ink

HF-RPA calculations with Gogny D1S interaction [PP]

Hidden in plain sight

sheet under normal light

photons



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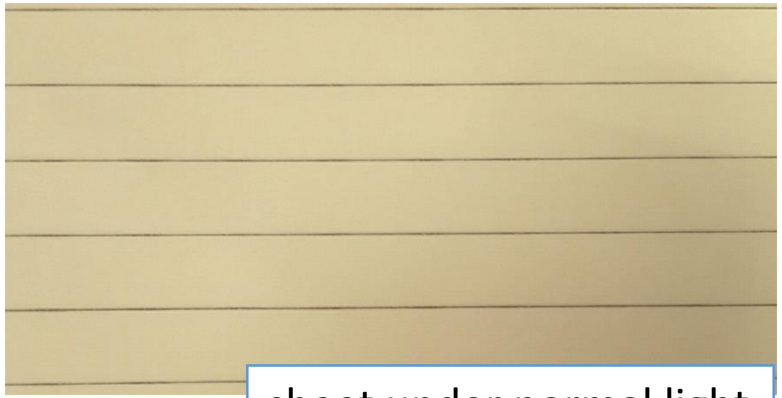
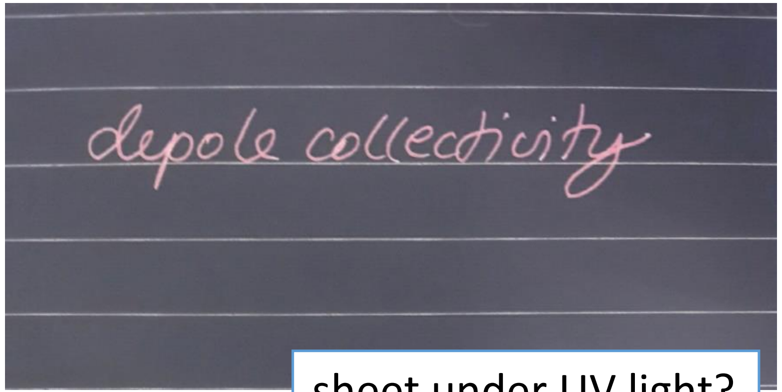
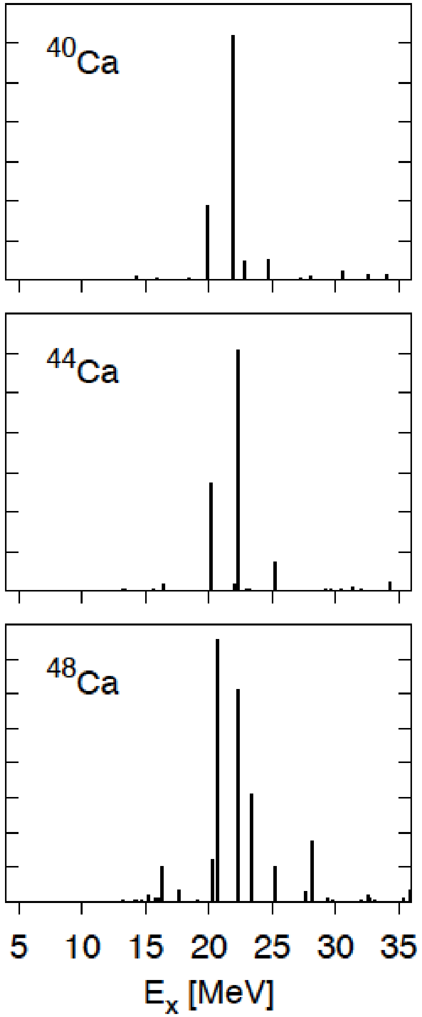


sheet under normal light



sheet under UV light?

photons



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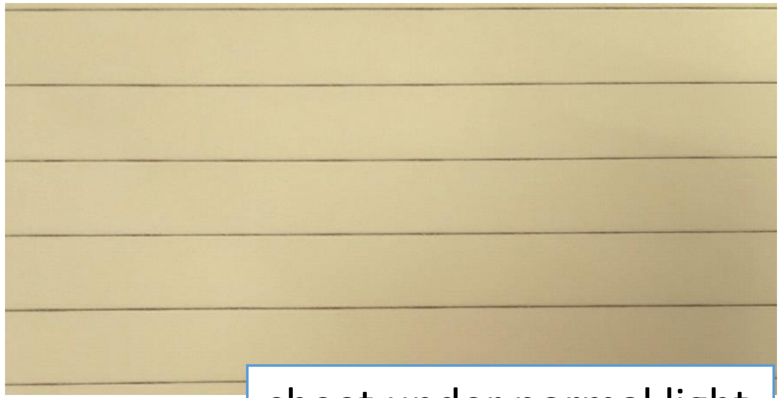

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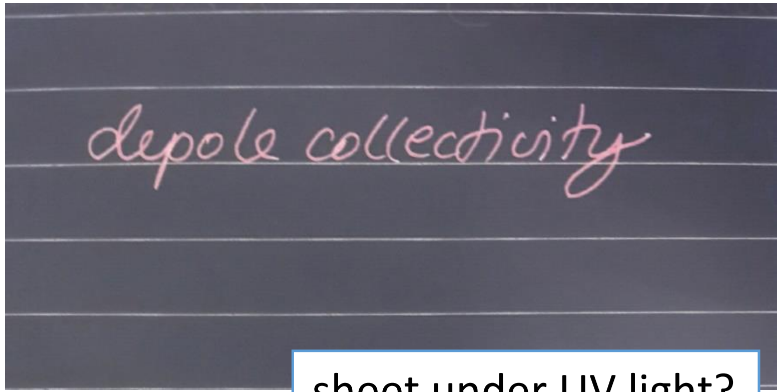
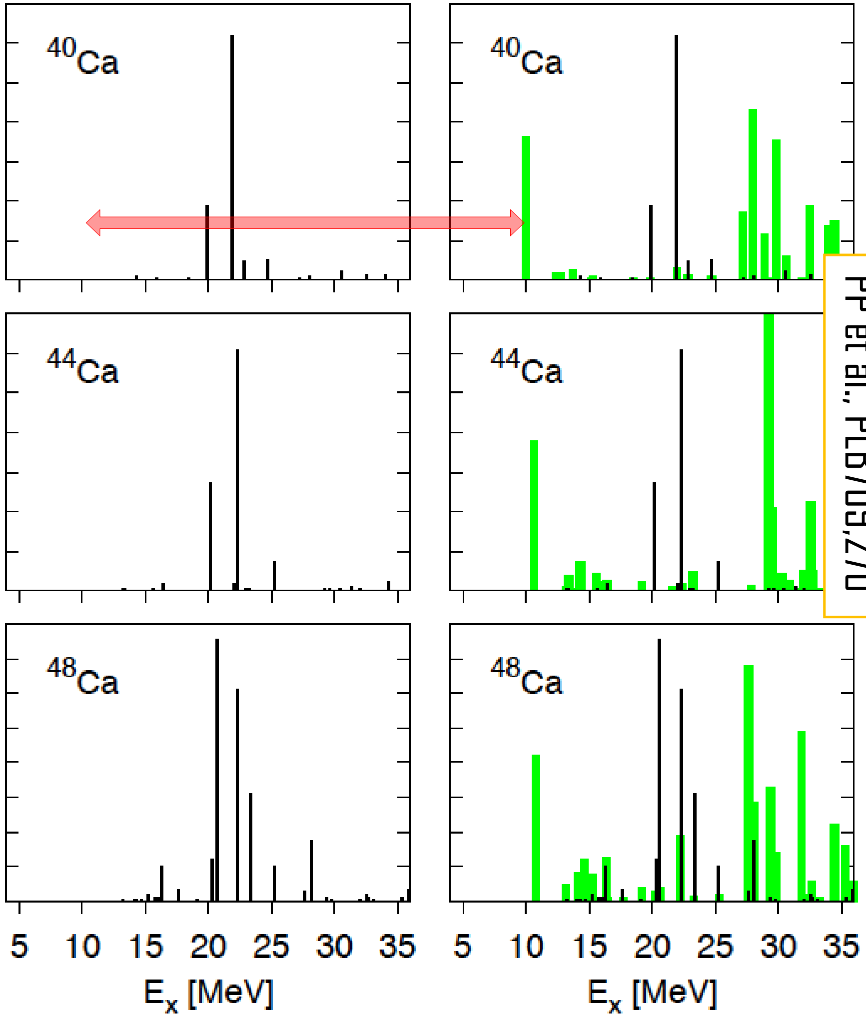


sheet under UV light?

photons

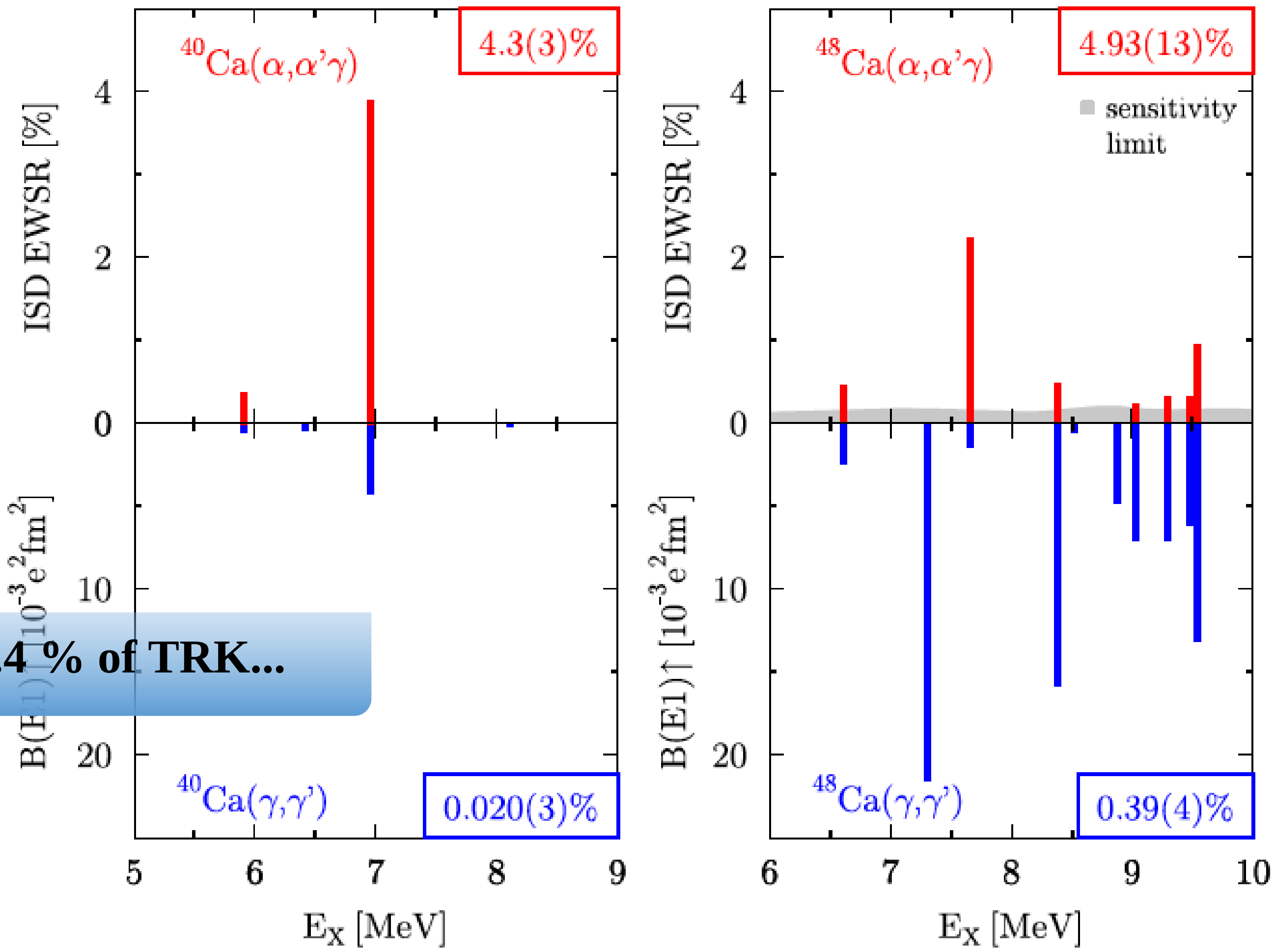
... and hadrons



PP et al., PLB709,270

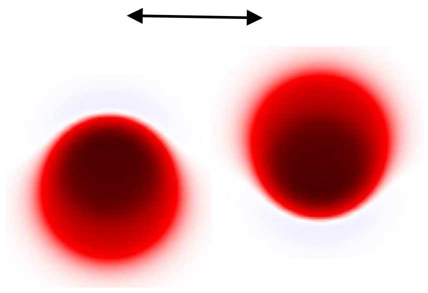
Low-energy dipole response of ^{40}Ca, ^{48}Ca

... but 4-5% of the IS EWSR



0.02 or 0.4 % of TRK...

V.Derya...,PP, et al., PLB730,288



Ca40: symmetric – IS and IV decoupled
Ca48: mixing What does this mean for 208Pb?

The misfit: Low-energy dipole vibration

- Aliases:
  - N=Z nuclei: “Isospin forbidden E1 transitions”
    - Isospin mixing make its γ-decay possible
    - Early attempts within the shell model failed to account for its decay rate (*1ħω not sufficient*)
  - N>Z nuclei: “Isoscalar segment of pygmy resonance”
    - Described by RPA (linear response theory)
  - “Compressible” oscillations
    - Sum-rule approach, Deal (1973)
    - Harakeh et al. (80’s ff): The 1ħω IS dipole resonance
- IS-LED: “Isoscalar low-energy dipole” oscillation

Energy levels of ^{16}O [a])

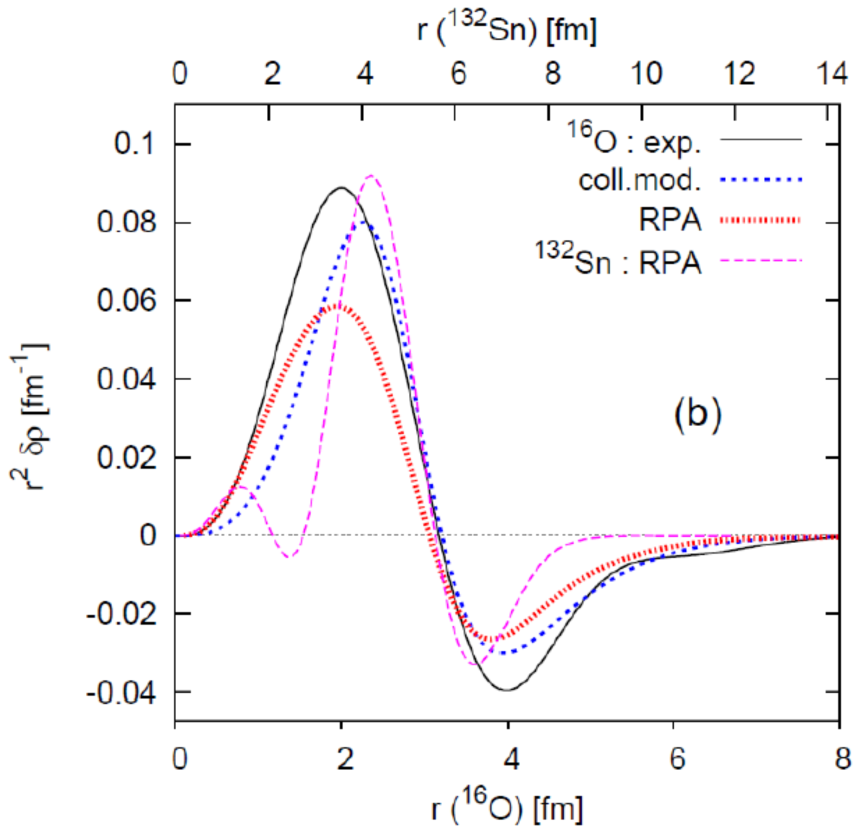
E_x (MeV ± keV)	$J^\pi;T$	K^π	$\Gamma_{c.m.}$ or τ_m (keV)	Decay
0	$0^+;0$		stable	
6.0494 ± 1.0	$0^+;0$	0^+	$\tau_m = 96 \pm 7$ psec	π
6.13043 ± 0.05	$3^-;0$		$\tau_m = 26.6 \pm 0.7$ psec $\lvert g \rvert = 0.55 \pm 0.03$	γ
6.9171 ± 0.6	$2^+;0$	0^+	$\tau_m = 6.6 \pm 0.4$ fsec	γ
7.11685 ± 0.14	$1^-;0$		$\tau_m = 11.6 \pm 1.0$ fsec	γ
8.8719 ± 0.5	$2^-;0$		$\tau_m = 180 \pm 16$ fsec	γ, α
9.632 ± 21	$1^-;0$	0^-	$\Gamma_{c.m.} = 400 \pm 10$	γ, α
9.847 ± 3	$2^+;0$		0.625 ± 0.100	γ, α
10.355 ± 3	$4^+;0$	0^+	25 ± 4	γ, α
10.957 ± 1	$0^-;0$		$\tau_m = 8 \pm 5$ fsec	
11.080 ± 3	$3^+;0$		$\Gamma < 12$	γ
11.096 ± 2	$4^+;0$		0.28 ± 0.05	γ, α
(11.26) [b])	$(0^+;0)$		(2500)	(α)
11.520 ± 4	$2^+;0$		74 ± 4	γ, α
11.60 ± 20	$3^-;0$	0^-	800 ± 100	α

Nuclear Physics A375 (1982) 1–168

A universal nuclear phenomenon?

Transition density, form factor:

- Described well by RPA
  - Cf. e-scattering data for O, Ca
- Predicted similar from ^{16}O to ^{132}Sn



Data from MIT Bates: Buti et al., PRC33(1986)755
Calculations: PP et al., EPJA47(2011)14, PRC89(2014)034306

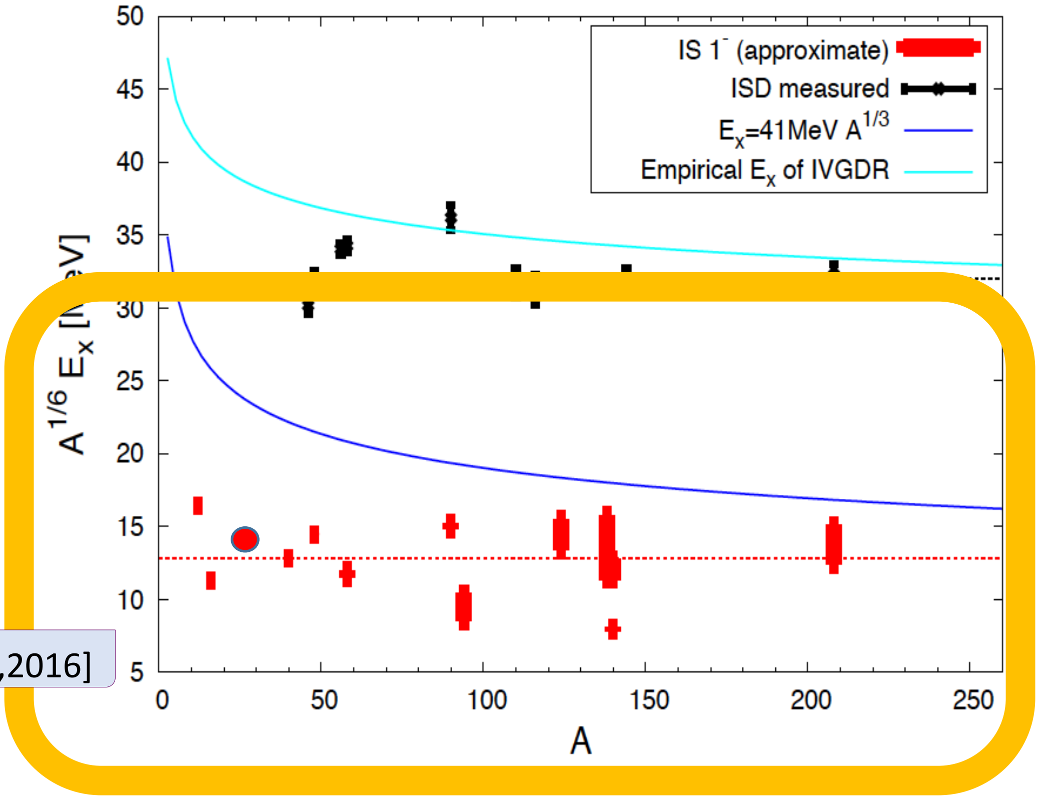
A universal nuclear phenomenon?

- But studies are spotty - Gaps to be filled!
  - Mapping along isotopic chains
  - Mapping along N=Z

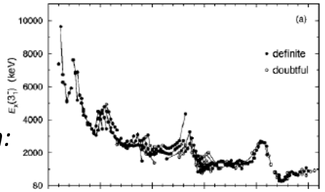
Data for IS dipole transitions from:
- Savran et al., Derya et al., Crespi et al., Poelhekken et al.,Harakeh et al

Theoretical investigations:
- [PP et al.; EPJA47,PLB709,PRC89,PRC92]: **N=Z up to ^{100}Sn; Ca, Sn, Ni, N=20**

Compilation: [PP,EXON,2016]



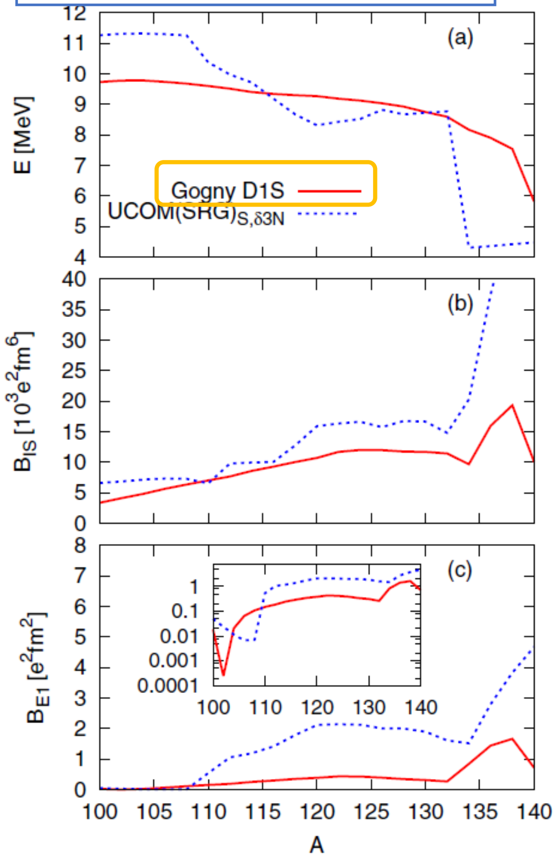
Compare situation with:



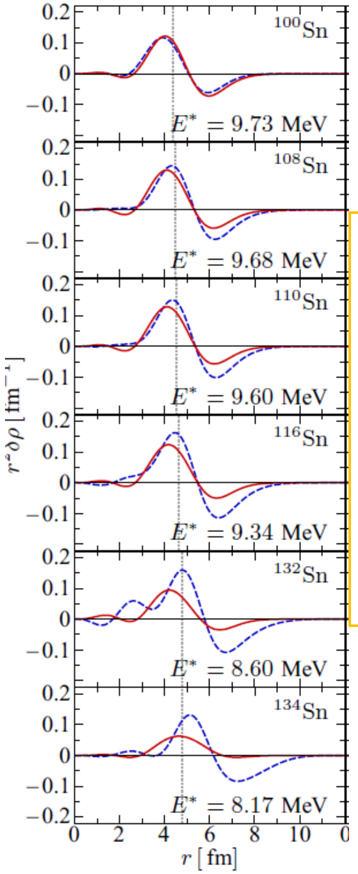
Mapping along isotopic chains

- Example: Ca isotopes
  - Smooth evolution from N=20 to 28; then dissolution to neutron modes [PP et al.,PLB709,270]
- Example: Ni isotopes
  - Bimodal structure mid-shell due to coupling with surface neutrons? [PP et al.,PRC92,034311]
- Example: Sn isotopes
  - Smooth evolution from N=50 to 82; then dominance of neutron configurations [PP et al.,PRC89,034306]

Sn: Energy and strength evolution



Transition density
- Blue: protons
- Red: neutrons



PP et al., PRC89,034306

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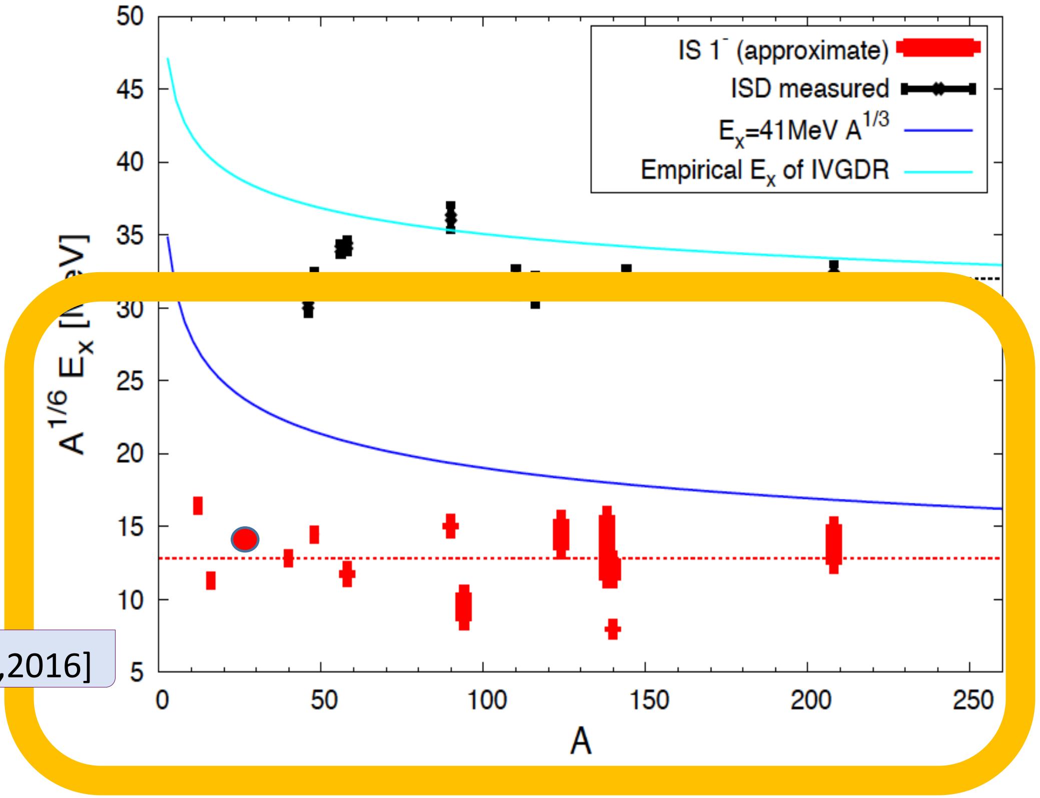
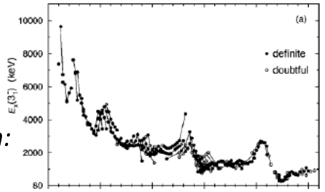
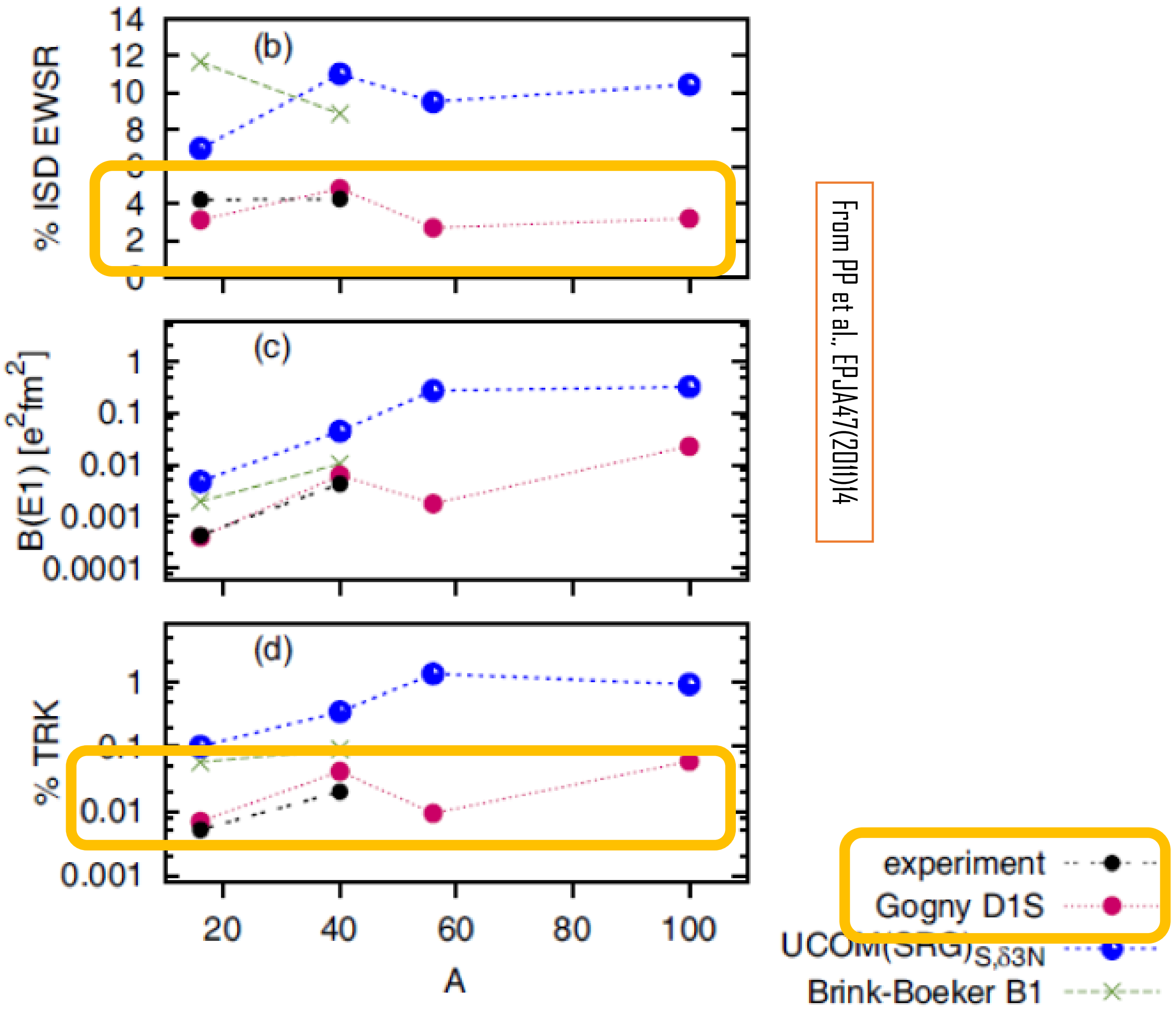


Compare situation with:



Discussion

The IS-LED of N=Z nuclei (and not only…)



Fiure 2: Properties of the IS-LED in closed-shell symmetric nuclei (from [Pap2011]). Black dots are experimental data. Colored points are predictions of various RPA models. Connecting lines are drawn solely to guide the eye.

Information on even-even N=Z nuclei with A=16~56

Basic information on the nuclei under discussion is shown in the following table. The main focus is beyond ^{40}Ca.

Energies are given in units of MeV. Blue color marks known collective IS-LEDs. Red color marks other plausible candidates. Other 1- states may belong to different deformed bands and provide complementary structure information.

Nucleus	^{16}O	^{20}Ne	^{24}Mg	^{28}Si	^{32}S	^{36}Ar	^{40}Ca	^{44}Ti	^{48}Cr	^{52}Fe [^{52m}Fe]	^{56}Ni
Half life	stable	stable	stable	stable	stable	stable	stable	51.9(3)Y	21.56(3)h	8.285(8)h	6.075(10)d
$E(2^+_1)$ B(E2)[Wu]	6.92 3.1	1.63 20.3	1.37 21.5	1.78 13.2	2.23 ?	1.97 8.2	3.90 2.26	1.08 13	0.75 31	0.85 14	2.70 5.8
$E(3^-)$ <8 MeV	6.13	5.62 7.16	7.62	6.88	5.01	4.18 5.86 6.84 7.26	3.74 6.28 6.58 6.93 7.69	3.18 3.92 5.06 5.42 7.34	4.06?	4.40 7.01	4.93? 7.58
$E(1^-)$ <8 MeV	**7.12**	5.79	7.55	?	5.80 7.43	5.84 ?	5.90 **6.95** 7.11?	3.76 6.22 7.50	?	6.88	6.01 7.14 (7.25?) (7.80?)
B(E1) [10^{-6} Wu]	**350**	8.3 (110 to 2+)	3.3	?	?	470	160 **1810**	44 ?	?		????
Spherical/ Deformed	S	D	D	D	(S)	D	S	(S)	D	D	D

Purely “toroidal”?
[Nesterenko et al., PRL120,182501+supplement]

Physics Letters B 278 (1992) 423–427

Low-energy isoscalar dipole strength in ^{40}Ca, ^{58}Ni, ^{90}Zr and ^{208}Pb

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The $1\hbar\omega$ low-energy isoscalar dipole strength has been studied in ^{208}Pb, ^{90}Zr, ^{58}Ni and ^{40}Ca, using the $(\alpha, \alpha'\gamma_0)$ reaction at 0°. The fraction of the isoscalar dipole EWSR exhausted by the observed 1^- states in the four nuclei is at maximum 14.7%, 8.0%, 5.0% and 4.3%, respectively.

strength in the excitation energy region of interest. So far information on the existence of $1\hbar\omega$ low-energy isoscalar dipole strength (ISLED, $\eta=0$, 1^-) in $A\geqslant40$ nuclei has been rather scarce. In this letter we present a systematic experimental study of this $1\hbar\omega$ component in $A\geqslant40$ nuclei. This is achieved by studying inelastic scattering of α-particles in which the isoscalar dipole cross section is at its maximum at very forward angles. By measuring in coincidence with the inelastically scattered α-particles the γ-decay to a 0^+ ground state, the characteristic α–γ angular correlation will allow unique identification of the multipolarity of the excited intermediate states.

The $(\alpha, \alpha'\gamma)$ experiment [5] was performed using a 120 MeV α-particle beam provided by the KVI AVF

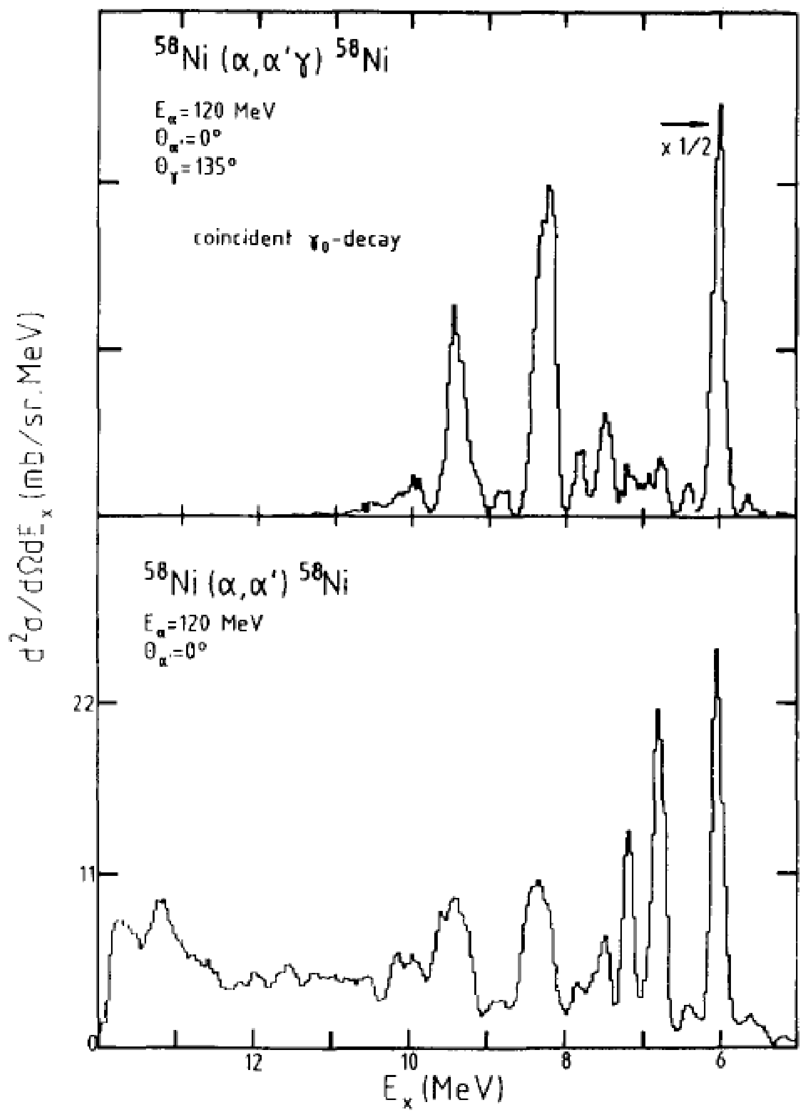

Fig. 2. The spectra of the ^{58}Ni(α, α′) and ^{58}Ni(α, α′γ) reactions at $\theta_{\alpha'}=0°$ and $\theta_\gamma=135°$. Note that the singles spectrum is nearly free of any instrumental background.

2.B: 2.L

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ISOSCALAR EXCITATIONS OF ^{24}Mg BY INELASTIC ^{3}He SCATTERING †

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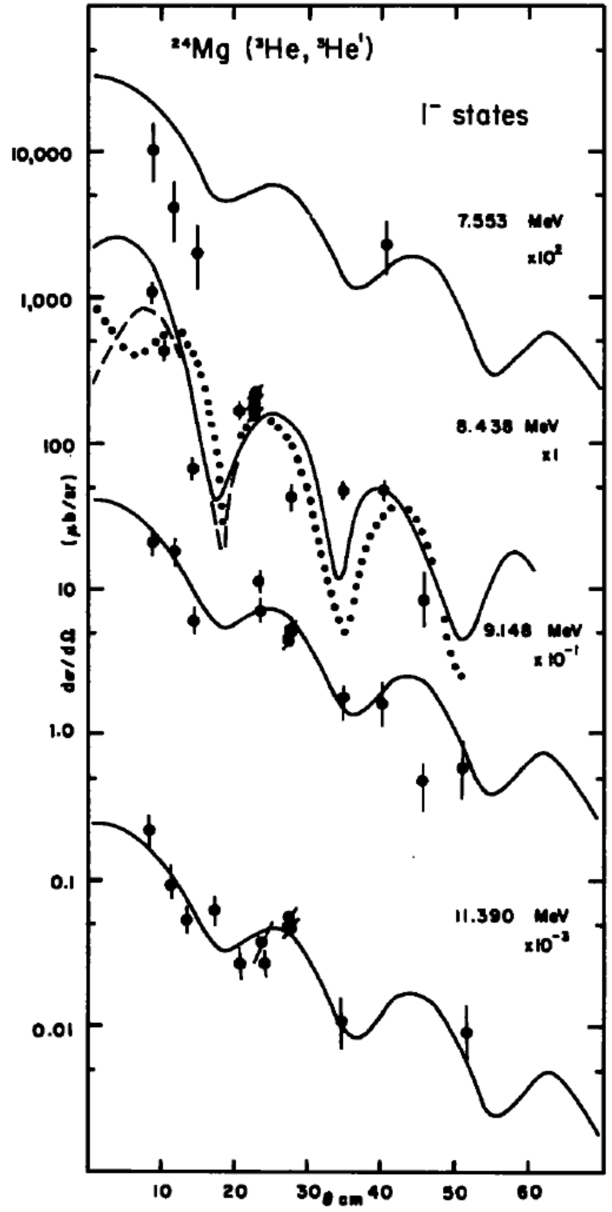
Abstract: The implications of a rotational model for ^{24}Mg are tested by inelastic ^{3}He scattering to almost all the known states below 11.5 MeV. Multiple excitation calculations are compared to the data for members of known or suspected rotational bands, particularly the 5^- and 6^+ states. Three examples of 0^+ excited states are studied, and a very strong excitation of the $T = 0$ 1^- state at 8.438 is found.



Thank you!

감사합니다~~

…Discussion …