Isoscalar and isovector dipole strength distribution in nuclei

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"COLLECTIVE MOTION IN NUCLEI UNDER EXTREME CONDITIONS"
COMEX5

Outline

- *1. General features of isovector excitations.*
- *2. The dipole resonance (isovector and isoscalar).*
- *3. The pygmy dipole states and the Schiff moment. (Time reversal violation experiments).*
- *4. Comments about the spin dipole resonance.*

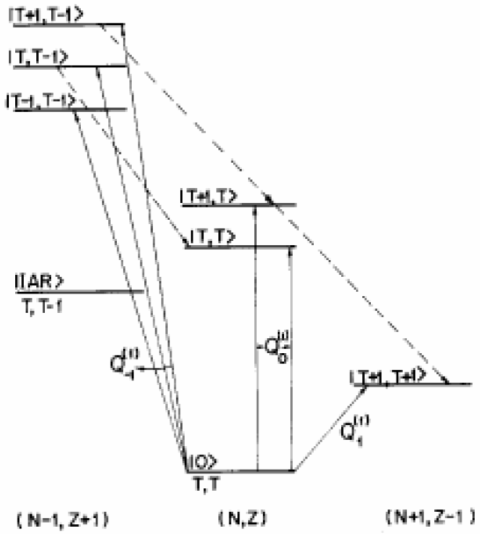
$\tau = 0$ (isoscalar) versus $\tau = 1$(isovector) excitations.

- In the case of $\tau = 0$ collective excitations the protons and neutrons move in phase. In the case of $\tau = 1$ excitations the protons move collectively out of phase with respect to the collective motion of neutrons.
- The isovector excitations are in general richer than the isoscalar ones.
- The τ=1 modes have three components, $\tau_z = 0, \pm 1$.
- The $\tau_z = 0$ case corresponds to pp^{-1}, nn^{-1} excitation
- The $\tau_z = -1$ describes pn^{-1} and the $\tau_z = +1$ the np^{-1} excitations.
- In nuclei with $N \neq Z$ the strength is split into several isospin components.
- When the isospin of the parent nucleus is T, the various isospin component are: in the $\tau_z = +1$ the isospin of the excitation is T+1, in the $\tau_z = 0$, excitations posses isospins T and T+1, while for the $\tau_z = -1$, the possible isospins are T-1, T, T+1.
- The energy splitting between the different components are such that the lower isospin excitation are also lower in energy.

Isospin splitting

- For nuclei with T>1 the lower isospin components contain more strength than the upper ones. For two reasons: the geometrical factors are larger and the collectivity is larger for the lower isospin components.
- The energy splitting carries information about the nuclear symmetry energy. Experimentally it is difficult to separate the various isospin components. As one goes to nuclei with a large neutron excess the splitting and strength differences grow. Exotic nuclei might help to observe this phenomenon.

Scheme of isovector transitions



- **For T> 1 the lower isospin states are more collective and carry more transition strength.**

Charge-exchange RPA.

- **All three directions of excitations are treated simultaneously. The first calculations of this type were done in the late seventies and early eighties. Skyrme interactions were used.**

PARTICLE–HOLE CALCULATION OF THE ISOBARIC ANALOG AND ISOVECTOR MONOPOLE RESONANCES

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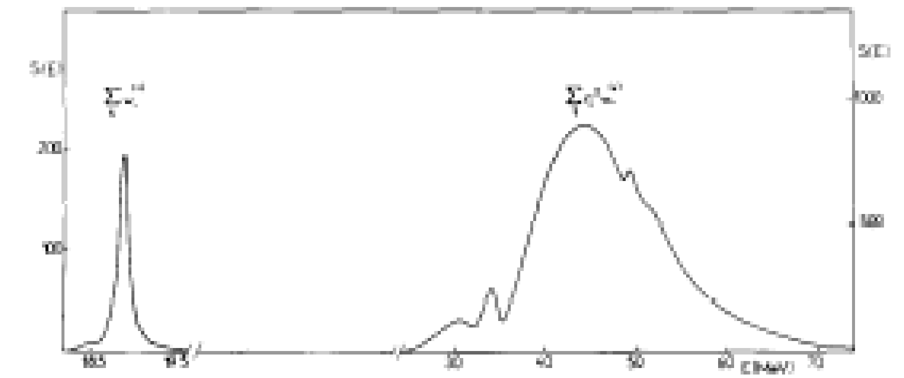

THE GIANT DIPOLE RESONANCE AND ITS CHARGE-EXCHANGE ANALOGS

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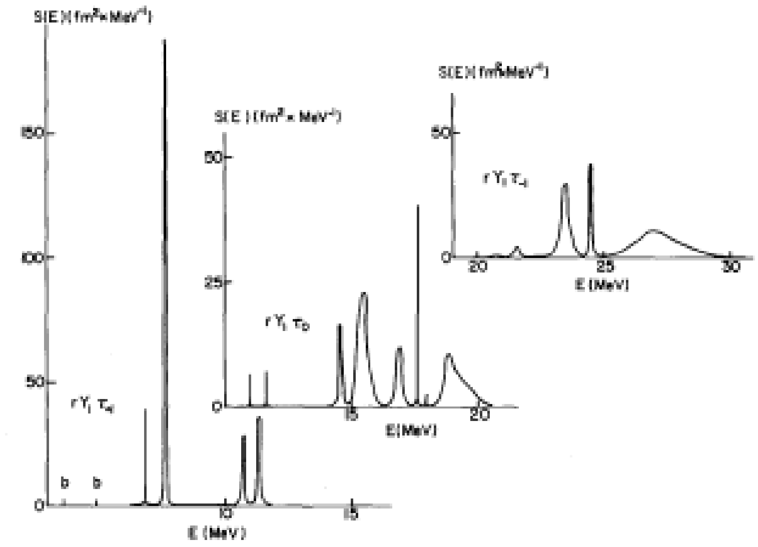

Fig. 1. Distribution of dipole strength in ^{90}Zr and its charge-exchange analogs calculated in the RPA.

The isovector dipole strength for all three components $\tau_z = \pm 1,0$ is calculated in the RPA. The properties of the charge-exchange modes are discussed

Collective excitation and basic symmetries

There is a close connection between collective nuclear motion and symmetries in the nuclear Hamiltonian. In some instances collective excitations are the result of the existence of certain symmetries in the system. One of the best examples is the isobaric analog resonance that results from the charge symmetry of the nuclear force. In other instances however collective excitations, such as giant resonances, serve as intermediate states in the process of breaking symmetries. (For example the isovector monopole resonance plays an important role in isospin mixing.)

Isoscalar dipole

- The “usual” isoscalar dipole transition induces a shift of the center mass of the nucleus. The higher order dipole transition operator of isoscalar type is defined as:

$$\mathbf{D} = \sum_i (r_i^2 - \frac{5}{3} < r^2 >)\mathrm{r}_i$$

The first measurements were performed in the eighties

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- Martin, G. P. A. Berg, W. Hurlimann, J. Meissburger, and J. G.
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- Among the first calculations were

N. Van Giai and H. Sagawa, Nucl. Phys. A 371, 1 (1981).

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More recent studies

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- **Andrea Carbone, Gianluca Colò, Angela Bracco, Li-Gang Cao, Pier Francesco Bortignon, Franco Camera, and Oliver Wieland Phys. Rev. C 81, 041301(R)**
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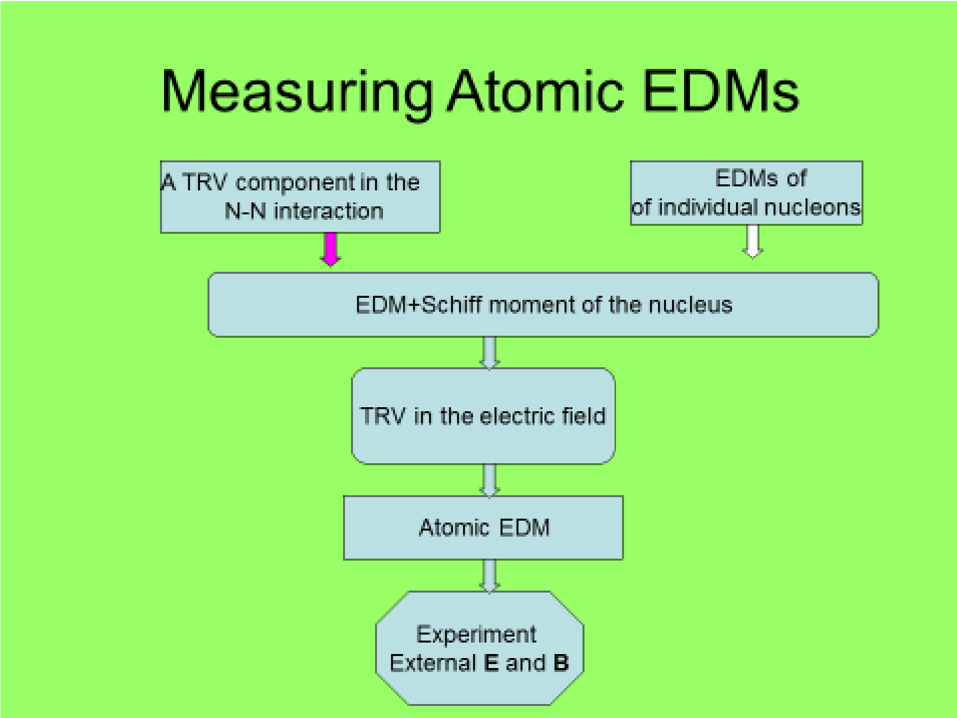
- **S. Shlomo and A. I. Sanzur, Phys. Rev. C 65, 044310 (2002).**

Time Reversal Violation (TRV) **and** the Dipole Moment

- In the absence of reflection symmetry violation or absence of time reversal violation, the static electric dipole moment of a quantum mechanical system, must vanish. One of the most effective ways to look for time reversal violation is to search for a dipole moment.

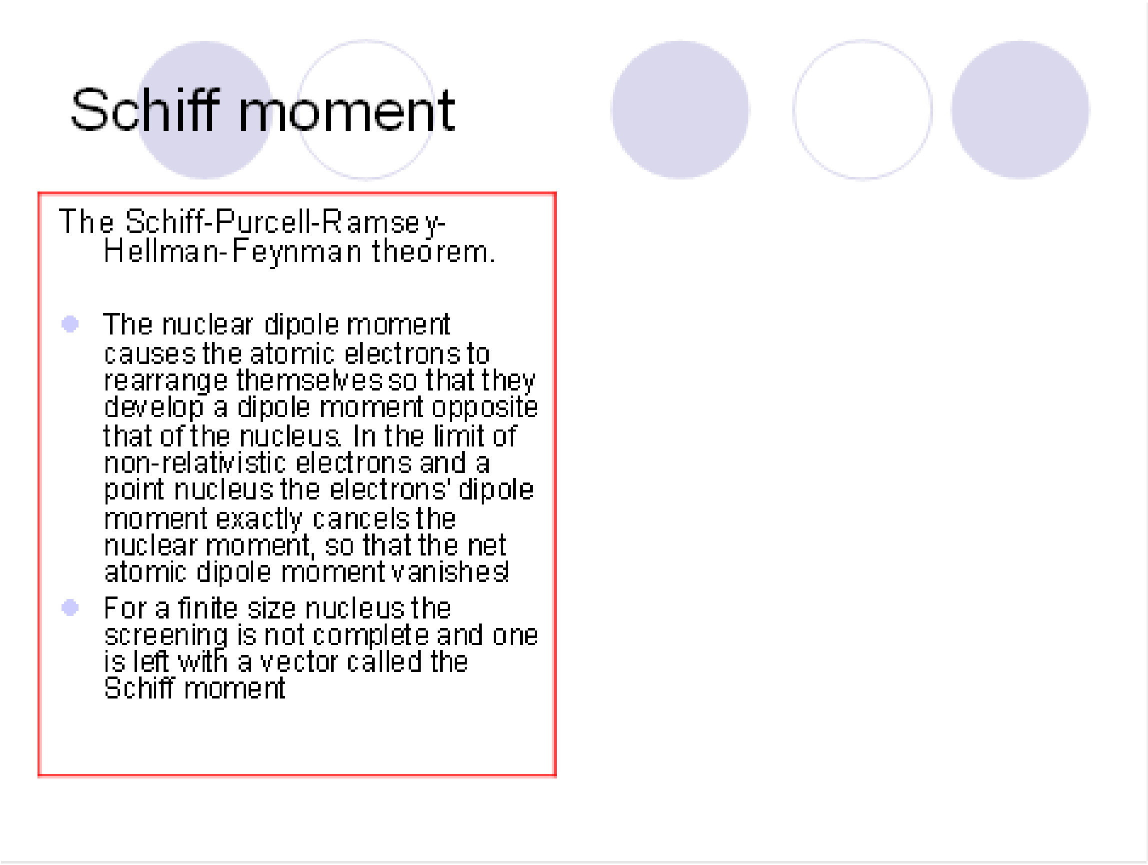
Tests of time reversal invariance



Schiff moment

- **Since the mean value of the nuclear dipole moment D is screened in the atom, the atomic electric dipole moment is generated by the nuclear *Schiff moment.***
  Apart from a normalization constant the Schiff operator is identical to the isoscalar dipole moment

$$\mathbf{S}=\frac{1}{10}\sum_i (r_i^2-\frac{5}{3}\langle r^2\rangle)\mathrm{r}_i$$



The role of the Schiff moment.

N.Auerbach and V. Zelevinsky. Phys. Rev. C86 045301 (2012).

The value of the Schiff moment is central to the measurement of time-reversal violation in an atom. One of the novelties in the study of nuclear resonances is the realization that some of the resonances have significant strength concentrated at lower energies, away from the main peak. These are referred to as the "pygmy resonances." It has been known for a long time that the ISD and the IVD have low-lying strength, around 10 MeV of the excitation energy, in many spherical nuclei. This means that the inverse energy-weighted sum (IEWS) of the strength distribution is particularly enhanced.

Particle+core in the odd-even nucleus

- $S \sim \frac{\langle 0^+ j\, j | S_z | 1^- j\, j^- \rangle \langle 1^- j\, j^- | V_{PT} | 0^+ j\, j \rangle}{\Delta E}$

- (The symbol j^- means the spin j but opposite parity)

IEWS

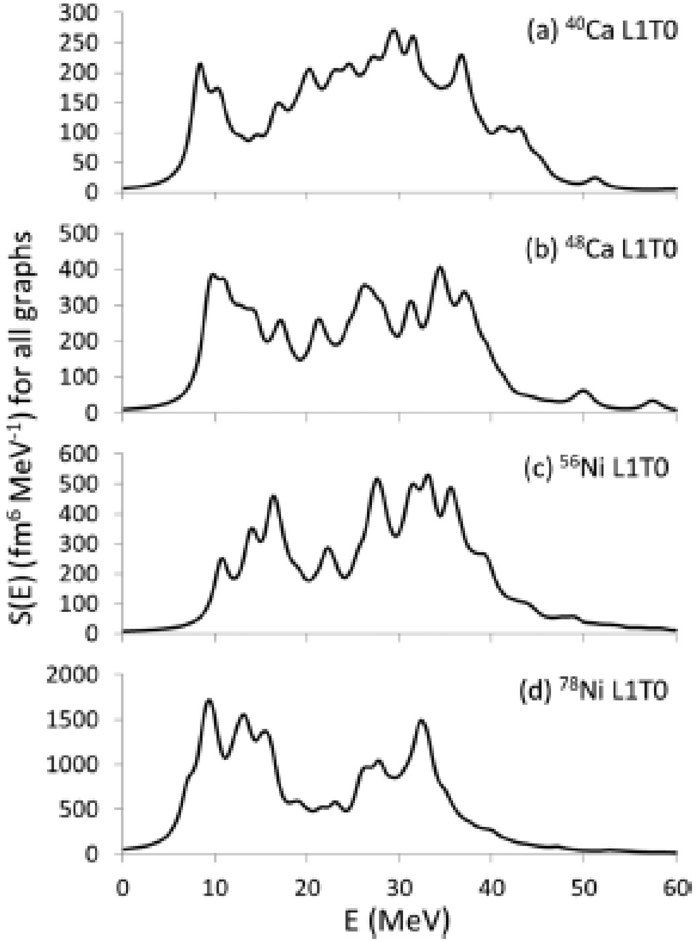
- For a weak interaction of the type:
- $V_{PT} = \xi(\mathbf{D} \cdot \vec{\sigma})$
- the S becomes proportional to the Inverse Energy Weighted Sum (IEWS)

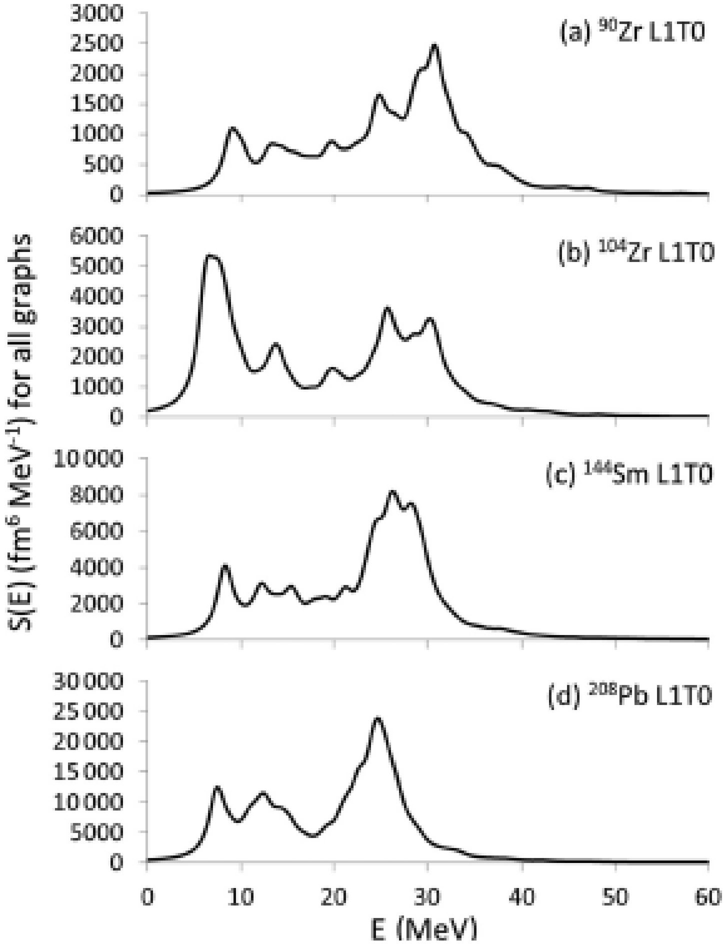
$$S = \frac{2}{3}\sqrt{\frac{j}{(j+1)(2j+1)}}\,\xi[S]\langle j\ell||\sigma||j\ell\rangle \times \sum_i \frac{|\langle 1_i^-||S||0^+\rangle|^2}{\Delta E_i}.$$

- Phys. Rev. C86, 045301, (2012).

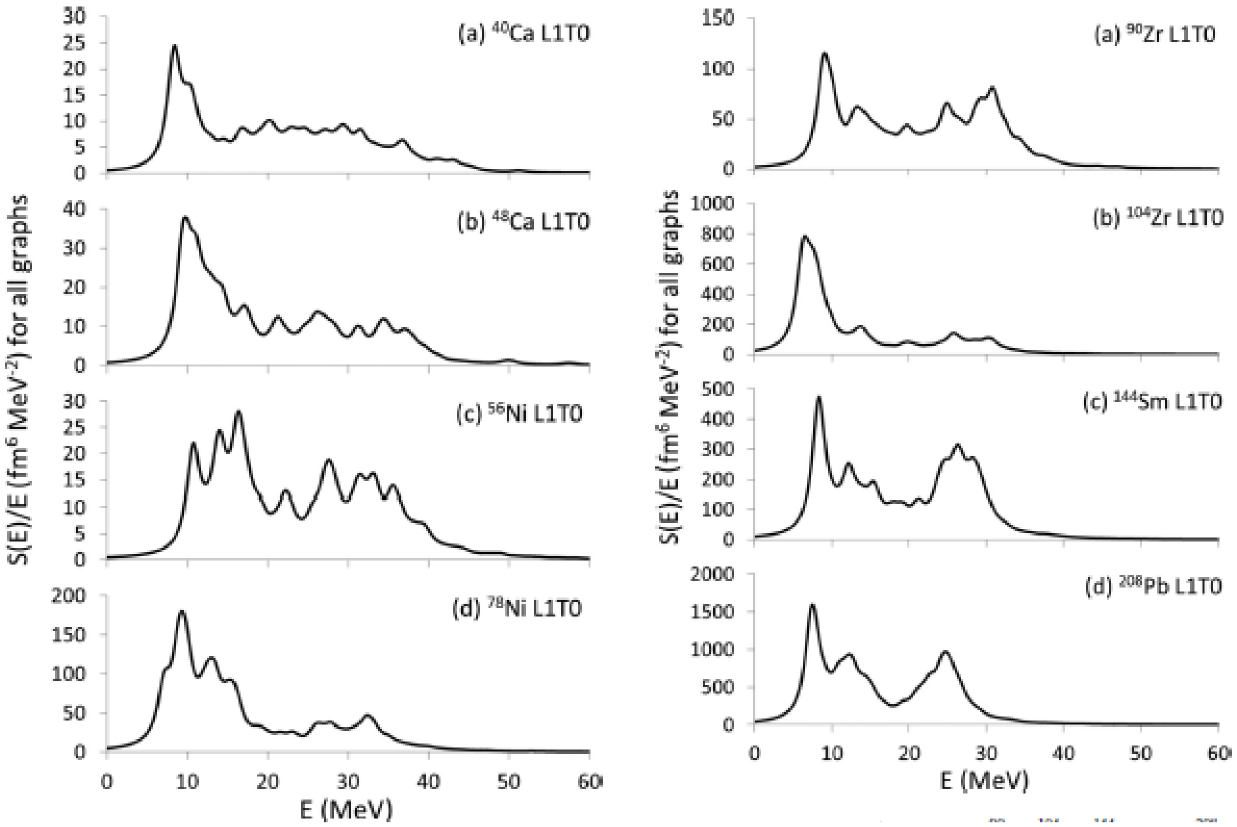
Isoscalar dipole strength

N.Auerbach, Ch. Stoyanov, M.RF. Anders and S. Shlomo, Phys. Rev. C89, 014335 (2014).





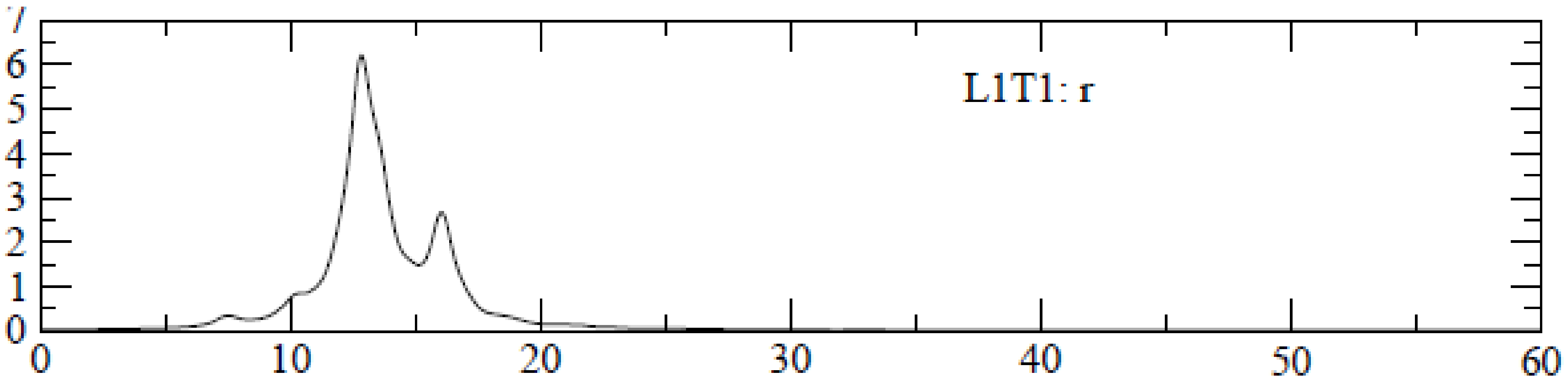
Inverse energy weighted strength



Inverse energy weighted sum for the isoscalar dipole strength

	$L1T0\ m_{-1}$
^{40}Ca	332
^{48}Ca	499
^{56}Ni	491
^{68}Ni	1326
^{78}Ni	2030
^{90}Zr	1708
^{96}Zr	3630
^{104}Zr	6069
^{100}Sn	1988
^{144}Sm	5853
^{208}Pb	17 737

Isovector dipole-r Pb 208



Isovector dipole

Andrea Carbone[1], Gianluca Colò[1,2], Angela Bracco[1,2], Li-Gang Cao[1,2,3,4],
Pier Francesco Bortignon[1,2], Franco Camera[1,2], and Oliver Wieland[2]

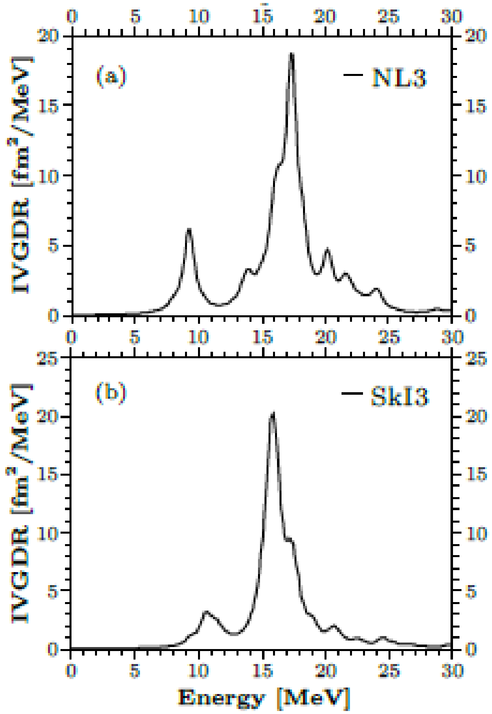


FIG. 1: Two typical dipole strength functions calculated in the nucleus ^{68}Ni. A nonrelativistic and a relativistic example are shown in panels (a) and (b) in which, respectively, the Skyrme force SkI3 and the NL3 parametrization of the effective RMF Lagrangian have been used. The sharp RPA peaks are averaged by using Lorentzian functions having 1 MeV width.

Contribution of the isoscalar dipole transition to the Schiff moment

- The contribution of the isoscalar dipole is of the same order or somewhat larger than the previously calculated (in a simple shell-model) results for spherical nuclei. One concludes that it is important to take into account the effect described here when trying to determine the limits of time reversal conservation.
- More work is needed in order to calculate more precisely this contribution.
- As one proceeds to neutron rich nuclei the low-energy dipole strength will increase. Experimental studies of such exotic nuclei as well as deformed nuclei is of interest.
- Experimental studies of charge-exchange reactions (single and double) will enrich the knowledge about isovector excitations.

- First Measurement of the Atomic Electric Dipole Moment of Ra225

R. H. Parker, M. R. Dietrich, M. R. Kalita, N. D. Lemke, K. G. Bailey, M. Bishof, J.P.Greene, R. J. Holt, W. Korsch, Z.-T. Lu, P. Mueller, T. P. O'Connor, and J. T. Singh

Phys. Rev. Lett. 114, 233002 – Published 9 June 2015.

Isovector spin dipole excitations

$$Q_{L,J,\mu}=i^{L+1-J}\sum_{i=1}^{A} f(r_i)[Y_L(\hat{r}_i)\times\vec{\sigma}(i)]_{J,0}\tau_\mu(i)\ ,$$

$$(\mu=0,\pm 1)$$

The probing operators are defined as follows:

$$Q_{1,J,\mu}=-(-1)^J\sum_{i=1}^{A} r_i[Y_1(\hat{r}_i)\times\vec{\sigma}(i)]_{J,0}\tau_\mu(i) \tag{3.5}$$

and the possible excitations may possess the spins $J^\pi=0^-,1^-,2^-$. The resulting total strengths, $m_{1,J,\mu}(0)$, and average excitation energies,

Nucleus	J^π	$\mu=+1$ $m_{1,J,+1}(0)$ (fm^2)	$\mu=+1$ $E_{1,J,+1}$ (MeV)	$\mu=0$ $m_{1,J,0}(0)$ (fm^2)	$\mu=0$ $E_{1,J,0}$ (MeV)	$\mu=-1$ $m_{1,J,-1}(0)$ (fm^2)	$\mu=-1$ $E_{1,J,-1}$ (MeV)
	0^-	19.2	12.5	130.3	20.3	266.1	32.1
^{208}Pb	1^-	20.2	7.6	108.3	16.9	233.3	29.5
	2^-	11.8	14.4	50.4	14.3	216.2	25.1

L=1, S=1, isovector

TABLE IV. The $L=1$, $S=1$ states: total strengths and average excitation energies for the different values of the angular momentum J.

Nucleus	J^{π}	$\mu=+1$: $m_{1,J,+1}(0)$ (fm^2)	$\mu=+1$: $E_{1,J,+1}$ (MeV)	$\mu=0$: $m_{1,J,0}(0)$ (fm^2)	$\mu=0$: $E_{1,J,0}$ (MeV)	$\mu=-1$: $m_{1,J,-1}(0)$ (fm^2)	$\mu=-1$: $E_{1,J,-1}$ (MeV)
^{60}Ni	0^-	26.9	18.9	31.6	26.0	36.6	32.7
	1^-	21.6	15.5	25.9	22.1	31.4	29.0
	2^-	10.6	12.1	18.0	17.4	21.4	24.5
^{90}Zr	0^-	28.2	12.5	41.5	22.7	60.4	31.8
	1^-	23.7	10.3	33.5	19.9	55.1	28.4
	2^-	12.7	9.1	24.9	16.6	42.9	23.5
^{208}Pb	0^-	19.2	12.5	130.3	20.3	266.1	32.1
	1^-	20.2	7.6	108.3	16.9	233.3	29.5
	2^-	11.8	14.4	50.4	14.3	216.2	25.1

- The $J=0^{-}$ component of the S=1, L=1 state is important in the calculation of parity violation. (N. Auerbach, Phys. Rev. C45, R514, (1992))

- The $J=1^{-}$ component of the S=1, L=1 state is involved in the determination of the anapole moment which is a parity violating but time reversal conserving moment. (N. Auerbach and B.A. Brown, Phys. Rev. **C60**, 025501, (1999))

- The $J=2^{-}$ component enters into the calculation of the parity and time reversal violating magnetic quadrupole moment.

Isovector dipole- overtone

- $\widetilde{\boldsymbol{D}} = \sum_i (r_i^2 - \frac{5}{3} < r^2 >)\boldsymbol{r_i \tau_i}$
- Isovector dipole-overtone

Inverse energy weighted sum rule

	$L1T0\ m_{-1}$	$L1T1\ m_{-1}$
^{40}Ca	332	53
^{48}Ca	499	67
^{56}Ni	491	76
^{68}Ni	1326	167
^{78}Ni	2030	203
^{90}Zr	1708	226
^{96}Zr	3630	465
^{104}Zr	6069	664
^{100}Sn	1988	269
^{144}Sm	5853	668
^{208}Pb	17 737	1806

TABLE III. Self-consistent HF-based RPA results for the inverse energy moment m_{-1} (fm^6 MeV^{-1}) of the ISD, obtained by using the probing operator of Eqs. (6) and (15), and of the IVD, obtained by using the probing operator of Eqs. (7) and (15) for a wide range of nuclei, calculated by using the KDE0v1 Skyrme interaction [25]. The excitation energy range of 0–60 MeV was used.

Paricle+core states in the odd-even nucleus

$$|0^+ \, 1/\, 2^+, 1/2^+\rangle$$
$$|1^- \, 1/2^+,\, 1/2^-\rangle$$

$$S = -\frac{\langle 1/2^+|S_z|1/2^-\rangle\langle 1/2^-|\hat{V}_{PT}|1/2^+\rangle}{\Delta E}$$

The Schiff moment is proportional to the isoscalar dipoleType equation here. transition matrix element:

$\boldsymbol{S} \sim \langle 0^+|\boldsymbol{D}|1^-\rangle$

Electric Dipole States and Time Reversal Violation in Nuclei.

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