Study of the isospin symmetry in N=Z nuclei

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EUNPC, Bologna 2-7/09/2018

Outline

- Isospin symmetry in atomic nuclei
- Isospin symmetry breaking
- Implications
- Giant Dipole Resonance
- Conclusions

Physics Background

Study of two "opposite" aspects of nuclear structure

Collective description

- All the nucleons are involved
- Deformation
- Vibration
- Rotation

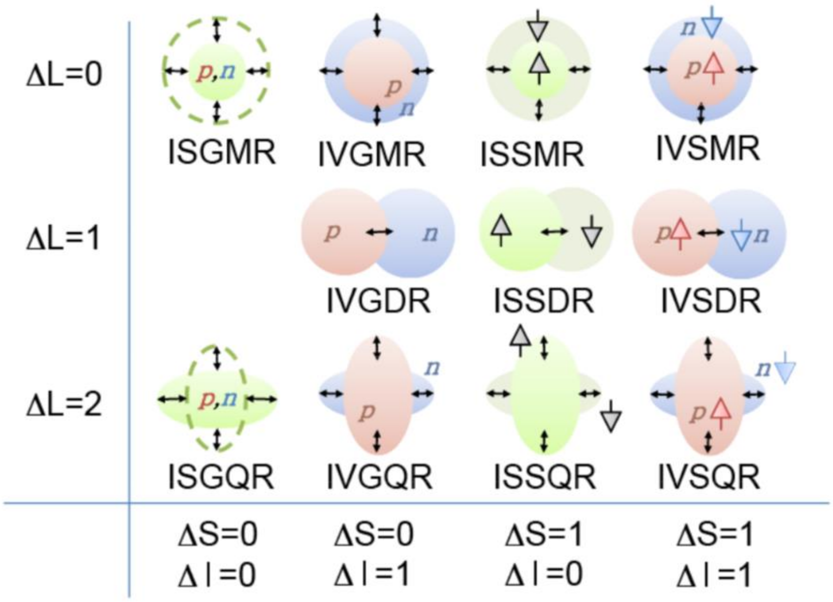
Single-Particle description

- Independent particles move in a central potential
- Shell structure
- Magic numbers

Physics Background

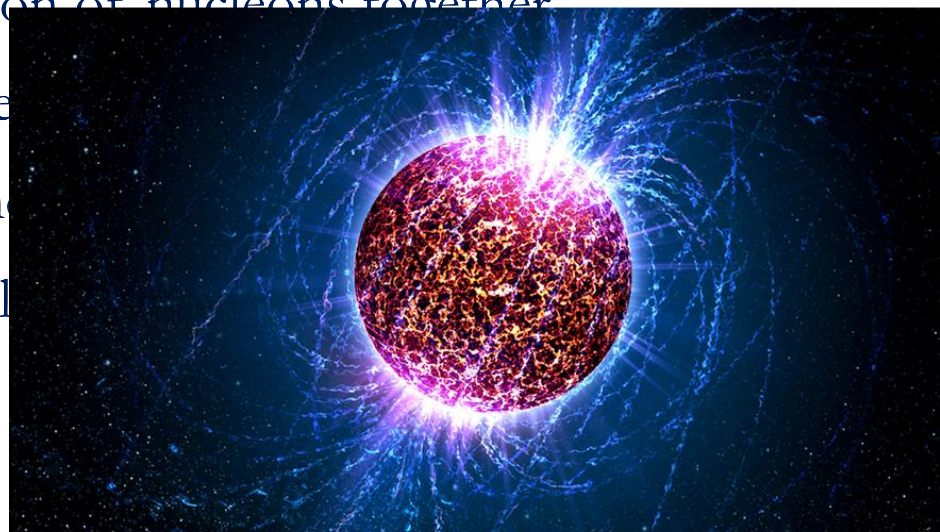
Giant Resonances:

- Coherent motion of nucleons together
- Motion involved charge, space and spin degree of freedom
- Giant Resonances like to fundamental properties of the nucleus
- IVGDR: Oscillation of protons against neutrons



Giant Resonances:

- Coherent motio[n of nucleons together]
- Motion involve ... om
- Giant Resonan ... nucleus
- IVGDR: Oscill



ΔI=1

Provide information on the **nuclear matter equation of state** (incompressibility, symmetry energy).
Equation of state used to describe neutron stars and supernova explosion.

ΔI=0 ΔI=1 ΔI=0 ΔI=1

Outline

- Isospin symmetry in atomic nuclei
- Isospin symmetry breaking
- Implications
- Giant Dipole Resonance
- Conclusions

The Isospin symmetry

Nuclear Interaction:

- Charge symmetry: **nn** interaction is the same as the **pp** interaction
- Charge independence: **np** interaction is also the same

⬇

Isospin symmetry: **neutrons** and **protons** can be considered as the same particle, **the nucleon**

The Isospin symmetry

NN experiments:

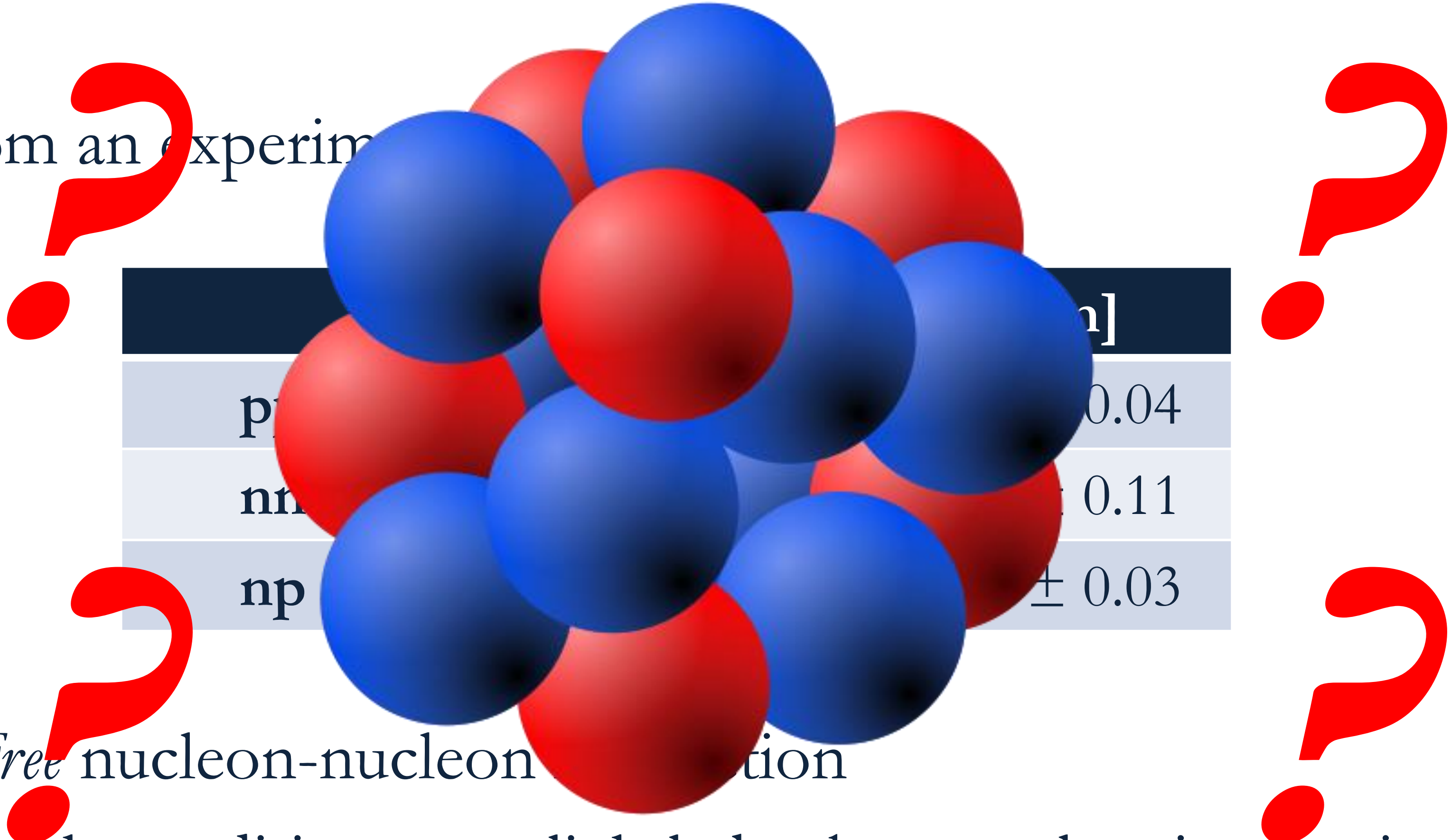
	a [fm]	r [fm]
pp	-17.3 ± 0.4	2.85 ± 0.04
nn	-18.9 ± 0.4	2.75 ± 0.11
np	-23.715 ± 0.015	2.73 ± 0.03

- *Free* nucleon-nucleon interaction
- Both conditions are slightly broken, nuclear interaction is more complicated.
- Charge-symmetry breaking → n,p mass difference (involves u and d quark)
- Charge-Independence breaking → pion-mass splitting

Lenzi, S.M., Bentley, M.A. Notes Phys. ***764****, 57-98 (2009)*
R. Machleidt, PRC 63, 024001 (2001)

The Isospin symmetry

From an experim



	n]
p	0.04
nn	0.11
np	± 0.03

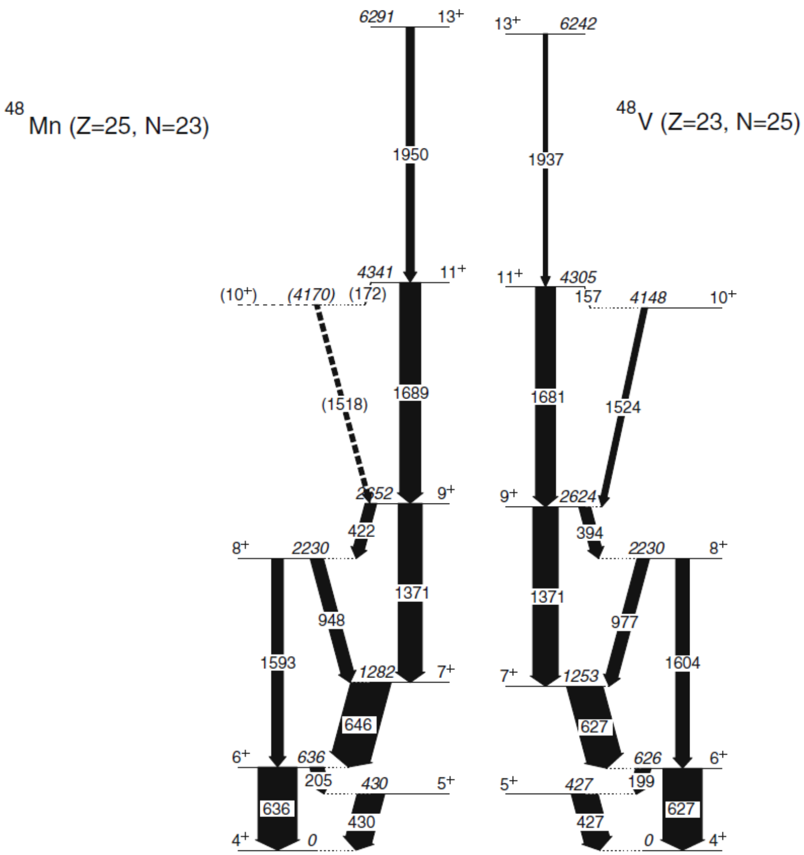
➢*Free* nucleon-nucleon tion

➢Both conditions are slightly broken, nuclear interaction is more complicated.

Lenzi, S.M., Bentley, M.A. Notes Phys. ***764****, 57-98 (2009)*

The Isospin symmetry

The nucleus is sensitive to the **effective nucleon-nucleon interaction** in the nuclear medium



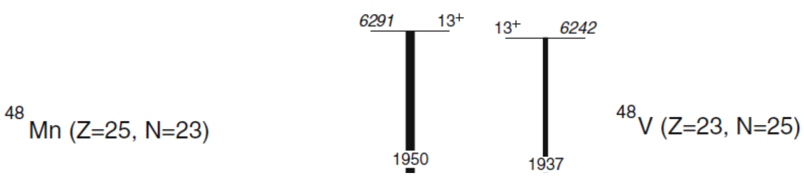
Mirror nuclei to check the isospin symmetry

The internal structure is **almost identical**

Lenzi, S.M., Bentley, M.A. Notes Phys. ***764****, 57-98 (2009)*

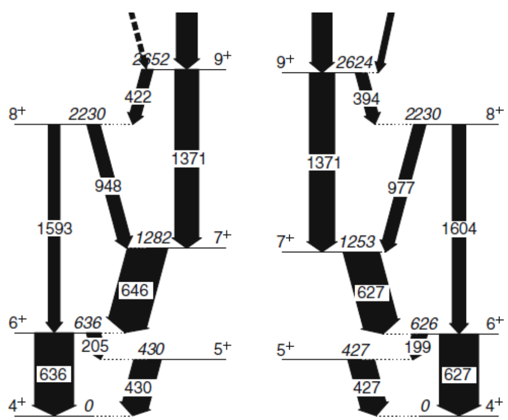
The Isospin symmetry

The nucleus is sensitive to the **effective nucleon-nucleon interaction** in the nuclear medium



Mirror nuclei to
check the isospin

What about the **Coulomb interaction** inside the nucleus??



almost identical

D. Warner, Bentley, Nature Physics **volume 2**, pages 311–318 (2006)

The Isospin-symmetry breaking

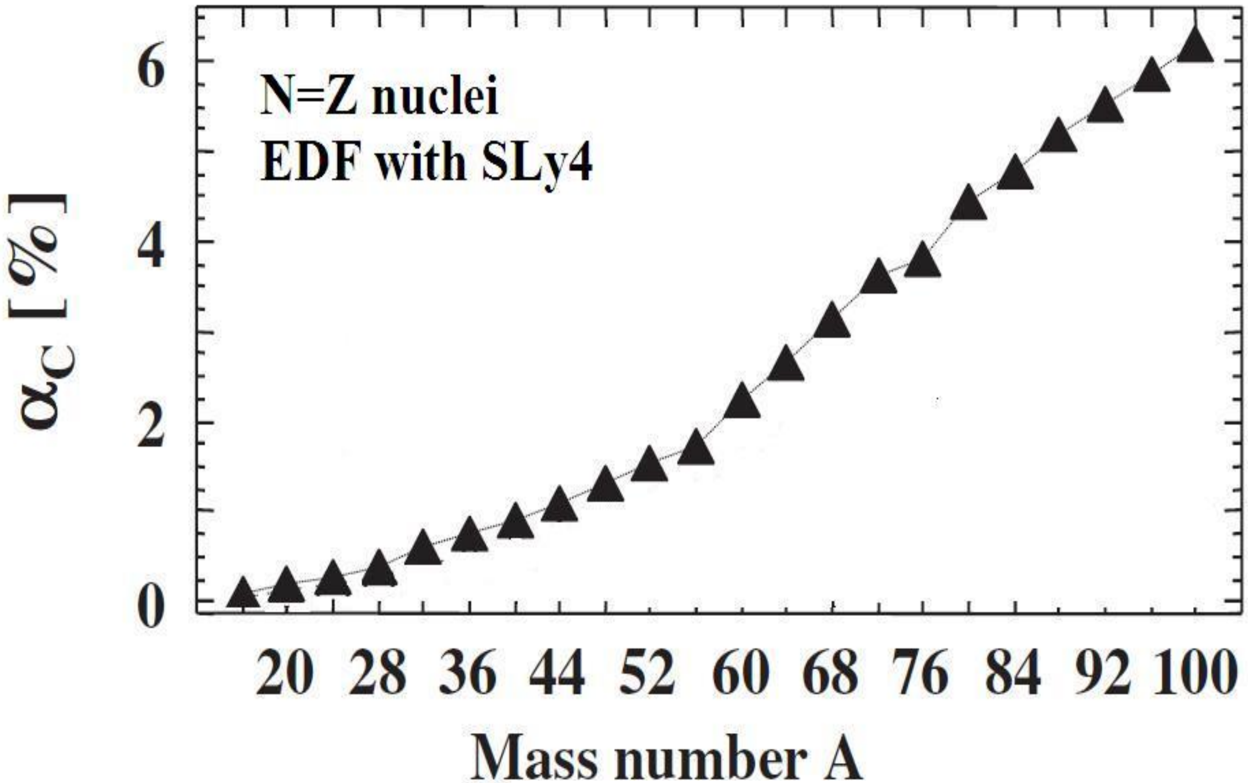
- The presence of the **Coulomb interaction** inside the nucleus causes a **mixing** between states with different isospin (***isospin mixing***)
- In a perturbative way the mixing probability in the nuclear ground state is defined as:

$$\alpha^2 = \frac{|\langle I=1|H_c|I=0\rangle|^2}{\Delta E^2}$$

$$|A\rangle = \beta|0\rangle + \alpha|1\rangle$$

G. Colo et al ., PRC 54 (1996) H. Sagawa et al PLB 444 1998. 1–6

The Isospin-symmetry breaking

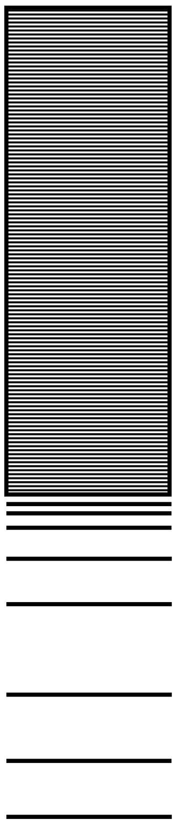


$$\alpha^2 = \frac{|\langle I=1|H_c|I=0\rangle|^2}{\Delta E^2}$$

Satula et al., PRL 103 (2009)

Isospin symmetry breaking

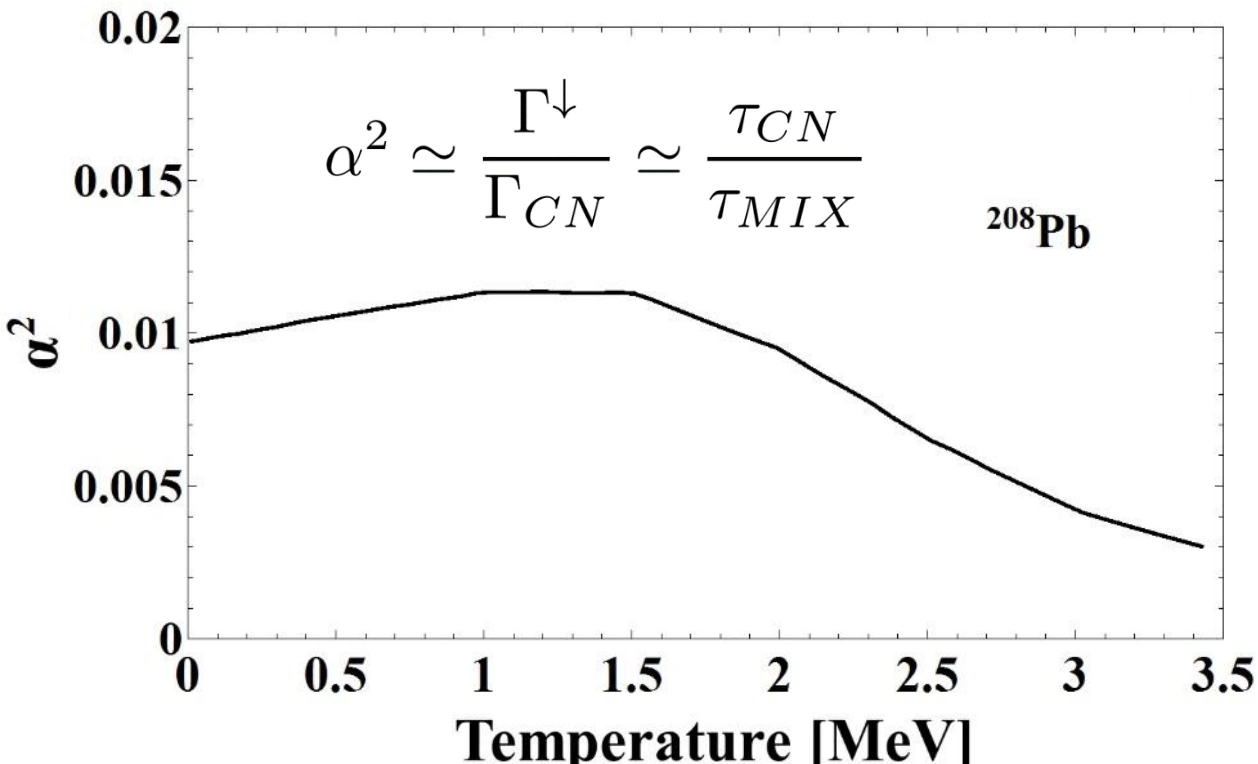
CN



- At high excitation energy the number of levels is very high. A=100 E*=50 MeV→ **10^{17} states/MeV**
- The nucleus has a **finite lifetime**
- **Mixing governed by the competition with the CN decay**
- The nucleus can decay **before** the mixing effects
- No mixing effects

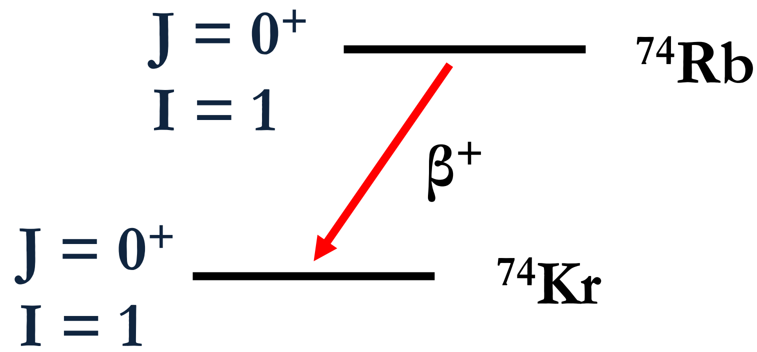
H. Morinaga, Phys. Rev. 97, 444 (1955)

Isospin symmetry breaking



- Competition between the decay and the mixing process
- At high **E***(or **T**) a better symmetry is expected
- **dynamical behavior**

G. Colo et al ., PRC 54 (1996) H. Sagawa et al PLB 444 1998. 1–6



$$0^+ \rightarrow 0^+, \Delta I = 0$$

Superallowed Fermi beta transitions

↓

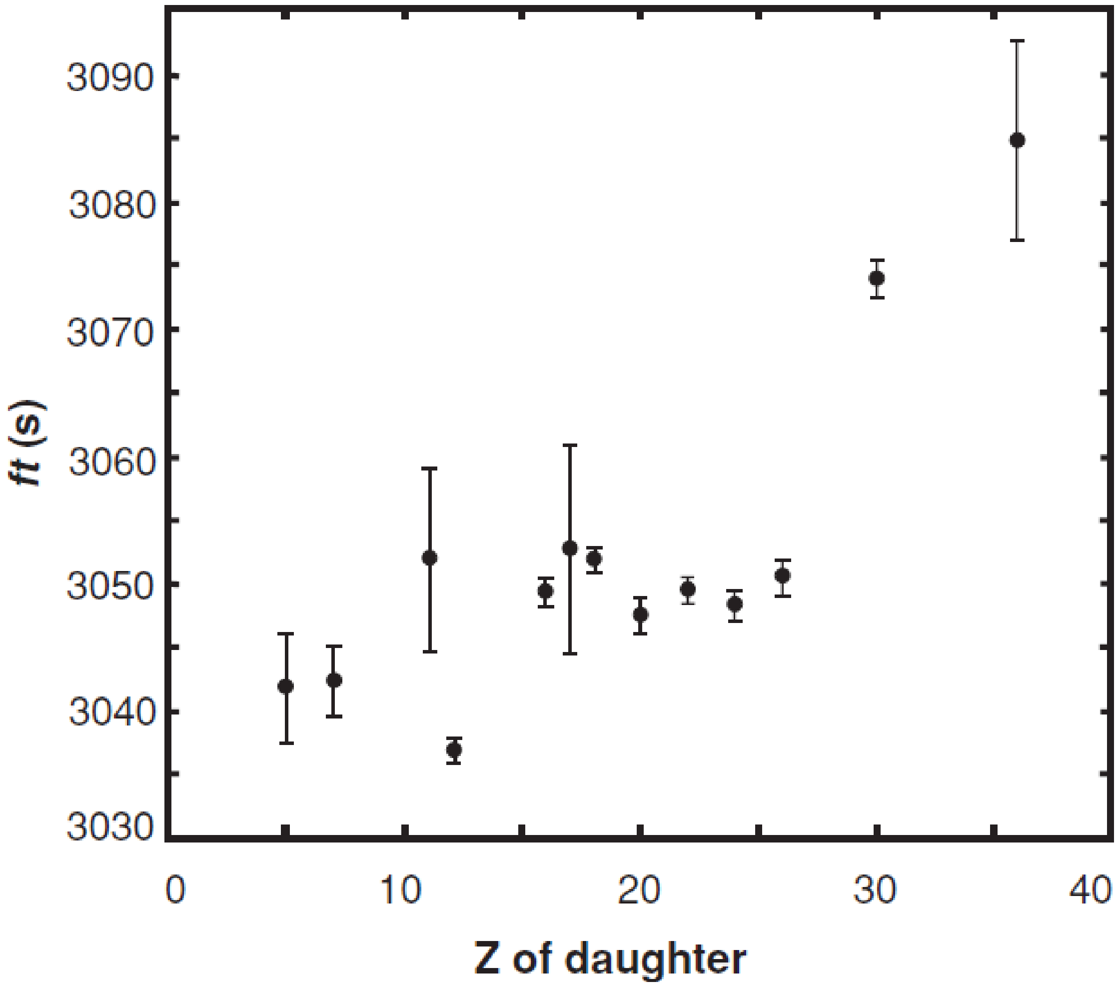
ft depends only on universal quantity.
It **<u>should</u>** be indiependent on the nuclear mass.

Universality of the vector coupling constant Gv

$$ft = \frac{K}{|M_F|^2 G_V^2} = \frac{K}{|M_F|^2 G_F^2 V_{ud}^2}$$

Measuring ft values in several nuclei one can extract <ft>
→ <Gv> & <Vud> & unitarity of CKM

Beyond nuclear structure: CKM matrix

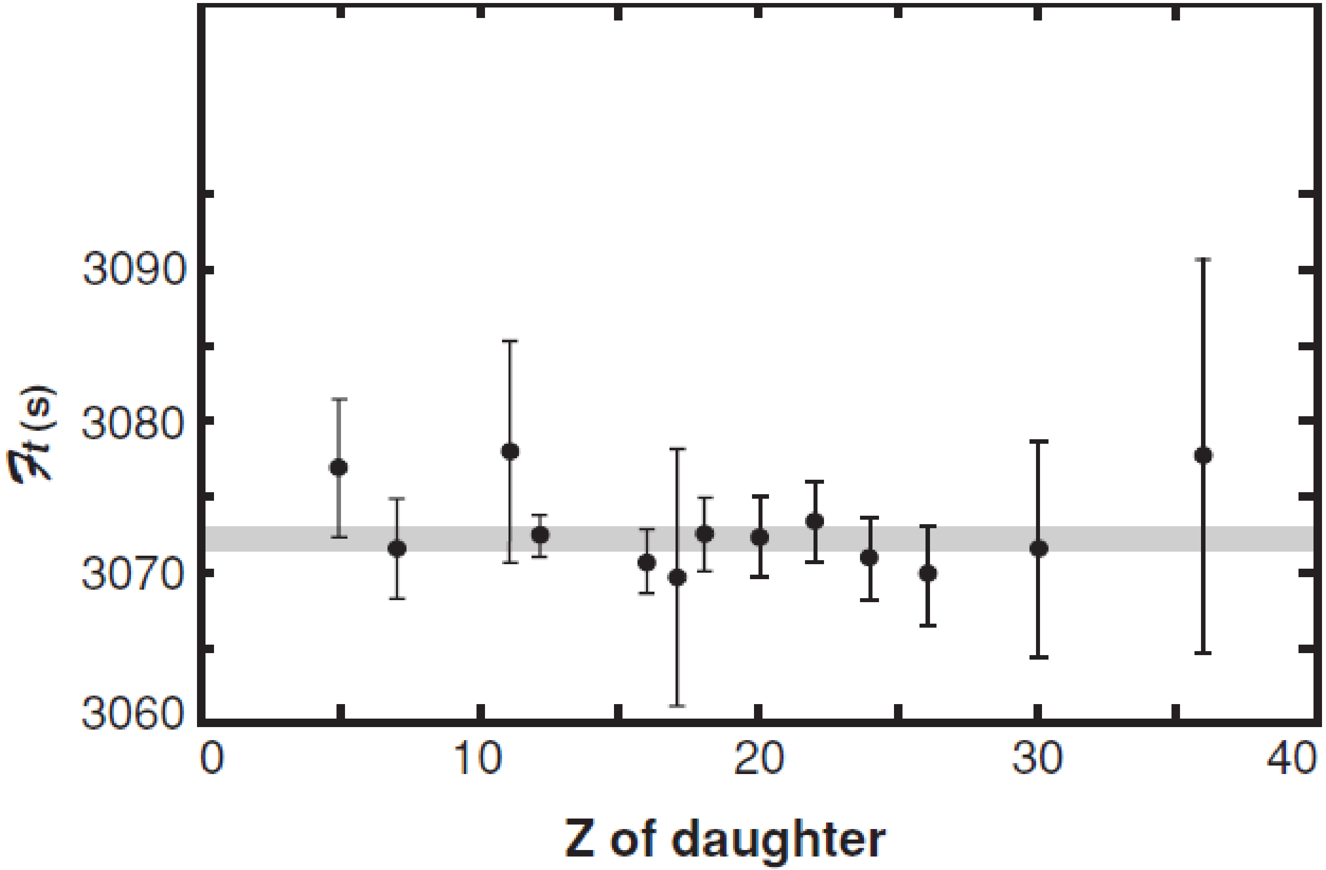


$$ft = \frac{K}{|M_F|^2 G_V^2} = \frac{K}{|M_F|^2 G_F^2 V_{ud}^2}$$

J.C. Hardy and I.S. Towner PRC 79, 055502 (2009)

Beyond nuclear structure: CKM matrix

$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$



Isospin Mixing plays a role in the determination of Vud

J.C. Hardy and I.S. Towner PRC 79, 055502 (2009), Nuclear Physics A844(2010)

Beyond nuclear structure

REVIEW ARTICLE

The role of isospin symmetry in collective nuclear structure

Nature Physics **Vol 2**, pages 311–318 (2006)

D. D. WARNER[1], M. A. BENTLEY[2]* AND P. VAN ISACKER[3]*

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[2]Department of Physics, University of York, Heslington, York YO10 5DD, UK
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PRL **116,** 102502 (2016) PHYSICAL REVIEW LETTERS week ending 11 MARCH 2016

Isospin Mixing Reveals $^{30}\mathrm{P}(p,\gamma)^{31}\mathrm{S}$ Resonance Influencing Nova Nucleosynthesis

M. B. Bennett,[1,2,3,*] C. Wrede,[1,2,†] B. A. Brown,[1,2] S. N. Liddick,[2,4] D. Pérez-Loureiro,[1,2] D. W. Bardayan,[5] A. A. Chen,[6] K. A. Chipps,[7,8] C. Fry,[1,2,3] B. E. Glassman,[1,2] C. Langer,[2,3] N. R. Larson,[2,4] E. I. McNeice,[6] Z. Meisel,[3,5] W. Ong,[1,2,3] P. D. O'Malley,[5] S. D. Pain,[7] C. J. Prokop,[2,4] H. Schatz,[1,2,3] S. B. Schwartz,[1,2,9] S. Suchyta,[4,2] P. Thompson,[8] M. Walters,[6] and X. Xu[1,2]

PHYSICAL REVIEW LETTERS **120,** 202501 (2018)

Nuclear Symmetry Energy and the Breaking of the Isospin Symmetry: How Do They Reconcile with Each Other?

X. Roca-Maza[*] and G. Colò[†]
Dipartimento di Fisica, Università degli Studi di Milano and INFN, Sezione di Milano, Via Celoria 16, 20133 Milano, Italy

H. Sagawa[‡]
RIKEN Nishina Center, Wako 351-0198, Japan
and Center for Mathematics and Physics, University of Aizu, Aizu-Wakamatsu, Fukushima 965-8560, Japan

Experimental technique

- Isospin is not a observable quantity to be measured
- Electromagnetic transitions and weak interaction can be used to test isospin invariance
- Searching for transitions that are forbidden by isospin conservation

Fermi β transition
(N≈Z nuclei)

E1 γ transition
(only in N=Z nuclei)

Experimental technique

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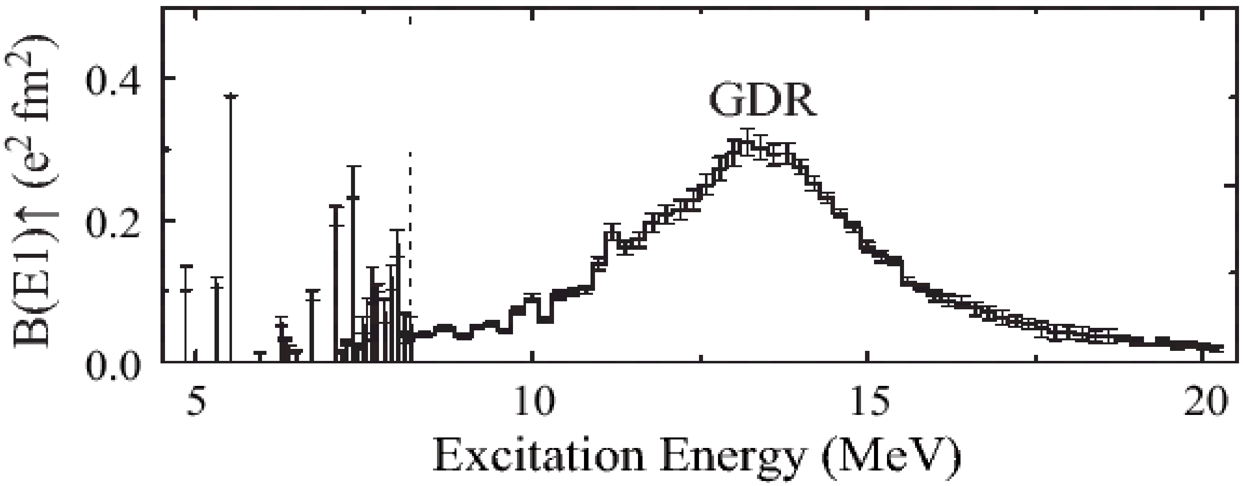
Fermi β transition
(N≈Z nuclei)

E1 γ transition
(only in N=Z nuclei)

Experimental technique

- ➢GDR is present in almost all nuclei
- ➢The B(E1) strength is concentrated in this resonance
- ➢Study of the gamma decay of the GDR



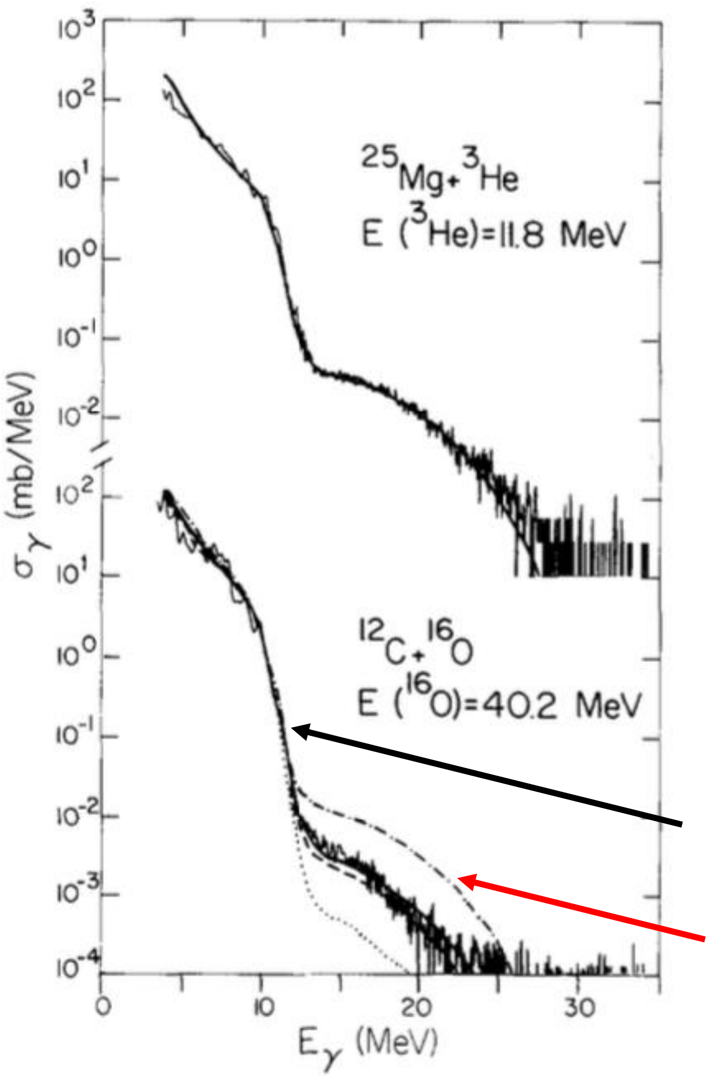
➢**GDR** is a perfect observable to investigate **E1 transitions**

J. A. Behr et al., Phys. Rev. Lett. 70, 3201 (1993)

M. N. Harakeh et al., Phys. Lett. B 176, 297 (1986)

S. Ceruti et al., PRL 115, 222502 (2015)

Experimental technique



- In N=Z (**I=0**) nuclei **E1 transitions** are suppressed
- Isospin **mixing increases the gamma-ray strength**

$$\sigma_\gamma \simeq [(1-\alpha_<^2)\frac{\Gamma_{\gamma<}}{\Gamma_<} + \alpha_<^2\frac{\Gamma_{\gamma>}}{\Gamma_>}]$$

Statistical gamma decay

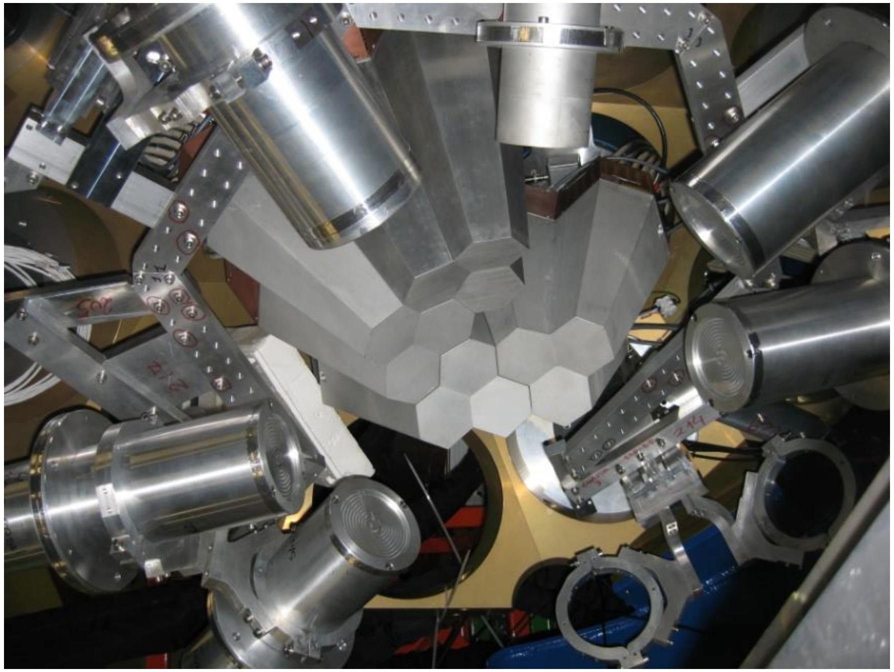
GDR gamma decay

M. N. Harakeh, PLB 176, 297 (1987)

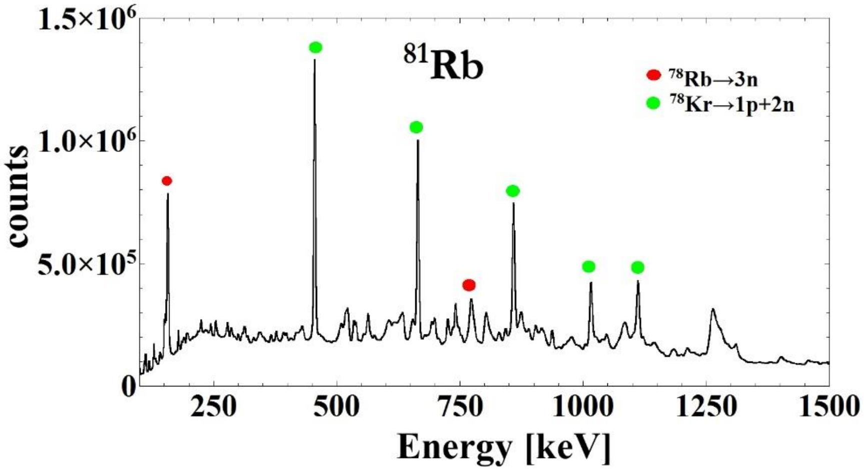
Experimental technique

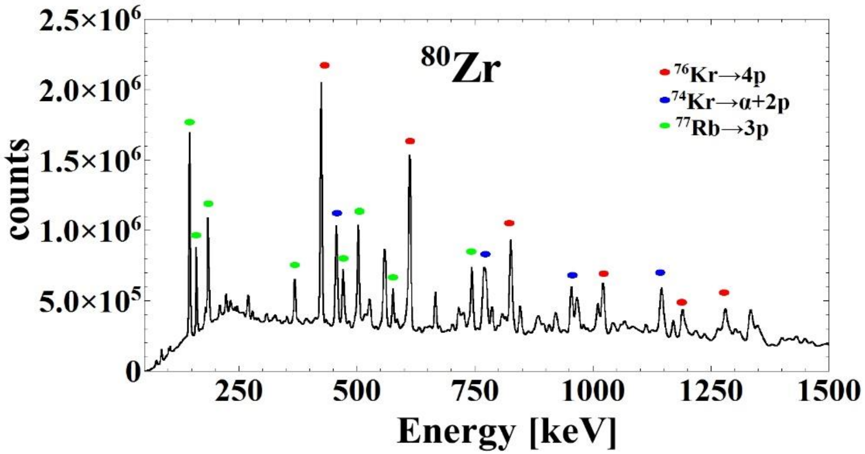
AGATA – HECTOR$^+$ array @ LNL

4 AGATA Clusters (12 capsules)
6 $LaBr_3$:Ce (3.5" x 8")
1 $LaBr_3$:Ce (3" x 3")



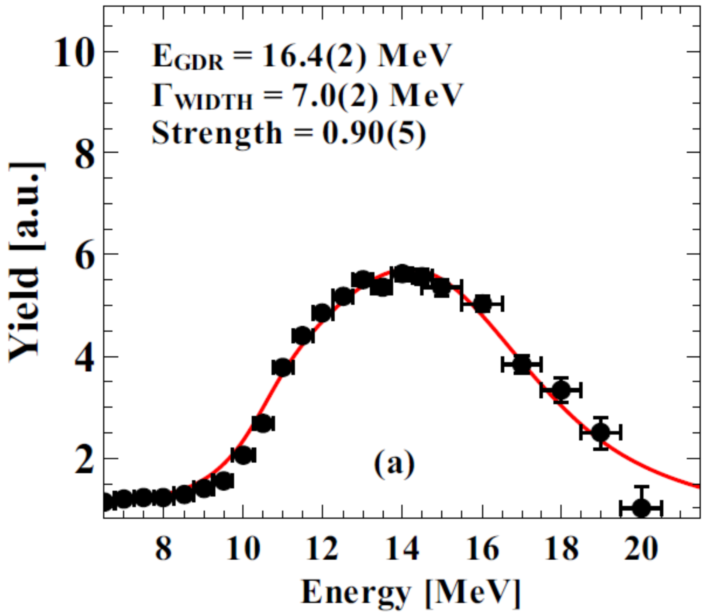
With **AGATA** we measure the evaporation residues to tune statistical model





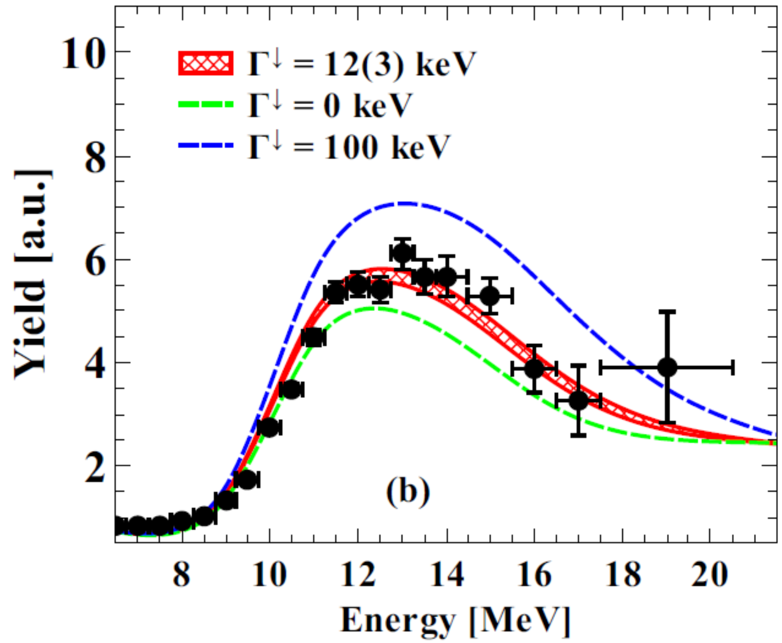
Experimental technique

^{81}Rb–HECTOR^{+}



$E_{GDR} = 16.4 \pm 0.2$ MeV
$\Gamma_{GDR} = 7.0 \pm 0.4$ MeV
S_{GDR} (%) $= 90 \pm 5$

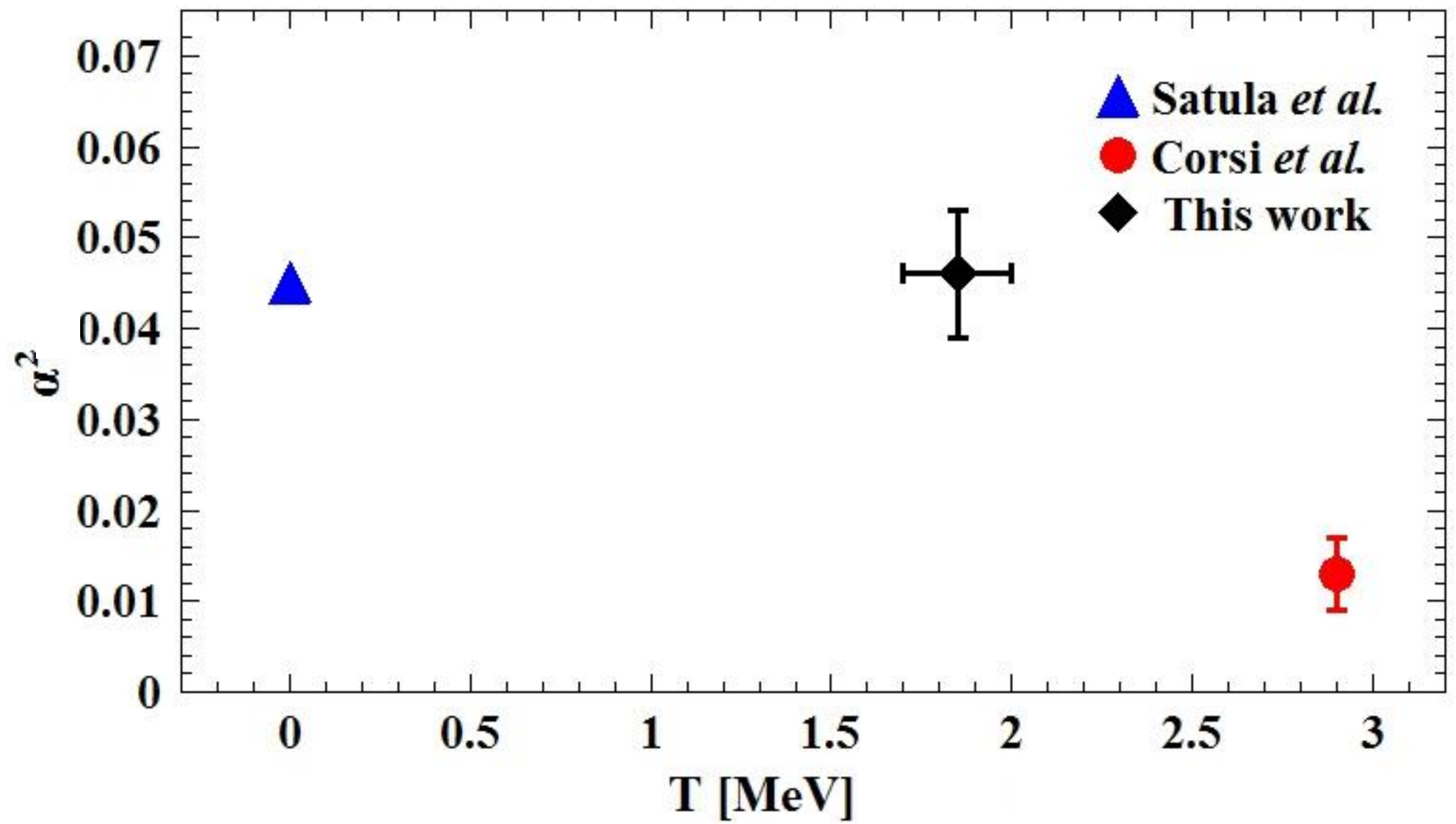
^{80}Zr–HECTOR^{+}



$\alpha^2 = 0.046 \pm 0.007$

S. Ceruti et al., PRL 115, 222502 (2015)

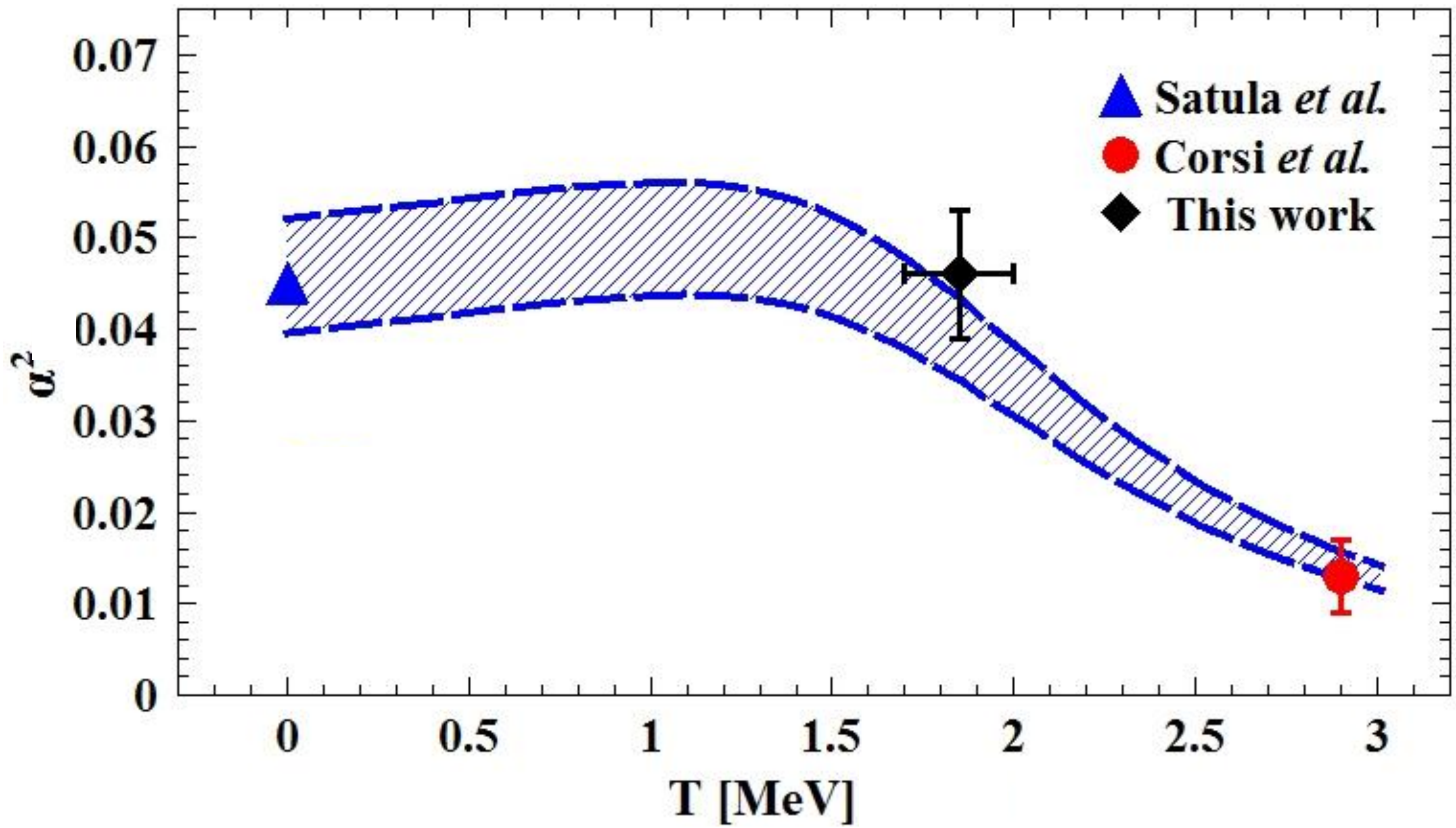
Experimental technique



Evidence of temperature dependence of α^2

Satula et al., PRL 103 (2009), S. Ceruti et al., PRL 115, 222502 (2015)
A. Corsi et al., Phys. Rev. C. 84, 041304(R) (2011)

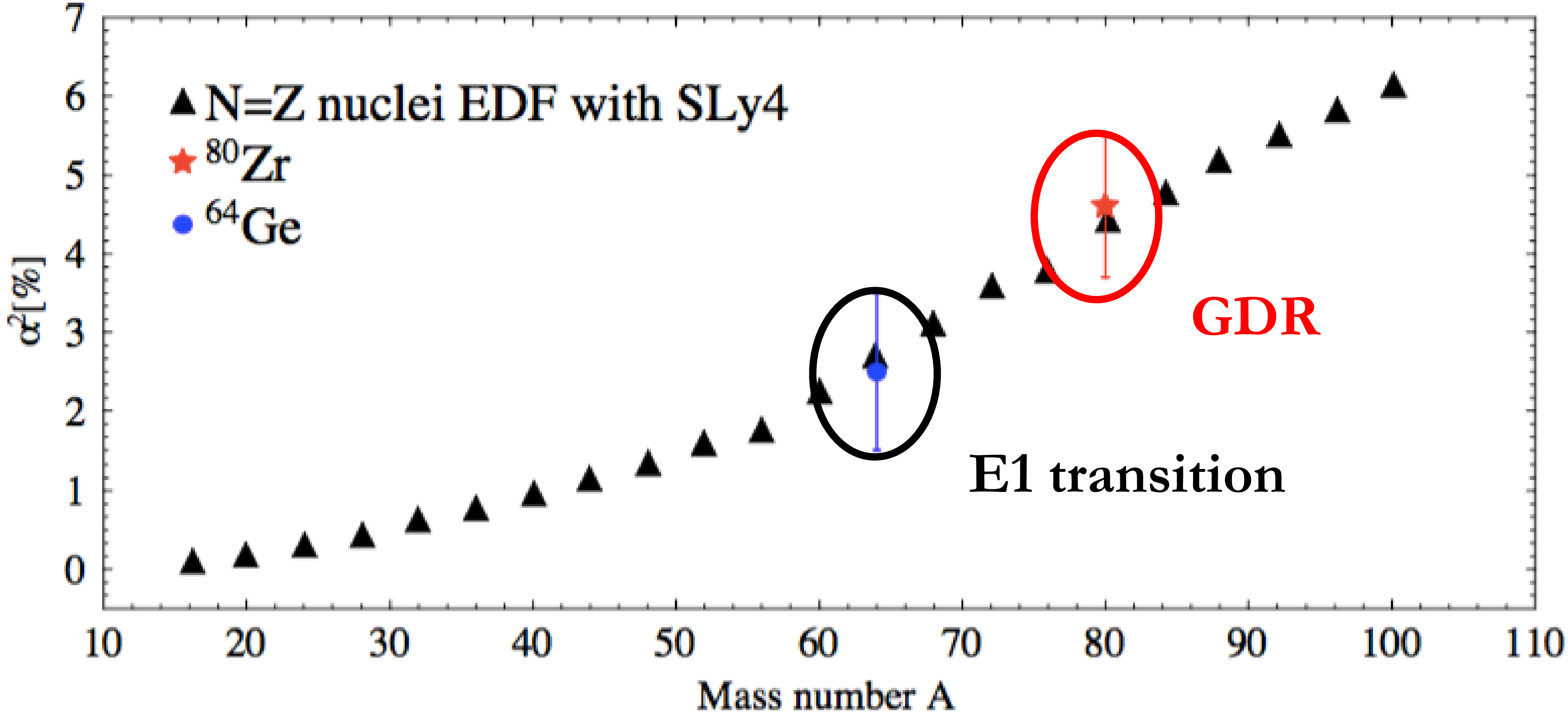
Experimental technique



$\alpha^2(T=0) = 4.6\% \pm 0.9\%$

Satula et al., PRL 103 (2009), S. Ceruti et al., PRL 115, 222502 (2015)
A. Corsi et al., Phys. Rev. C. 84, 041304(R) (2011)

Experimental technique



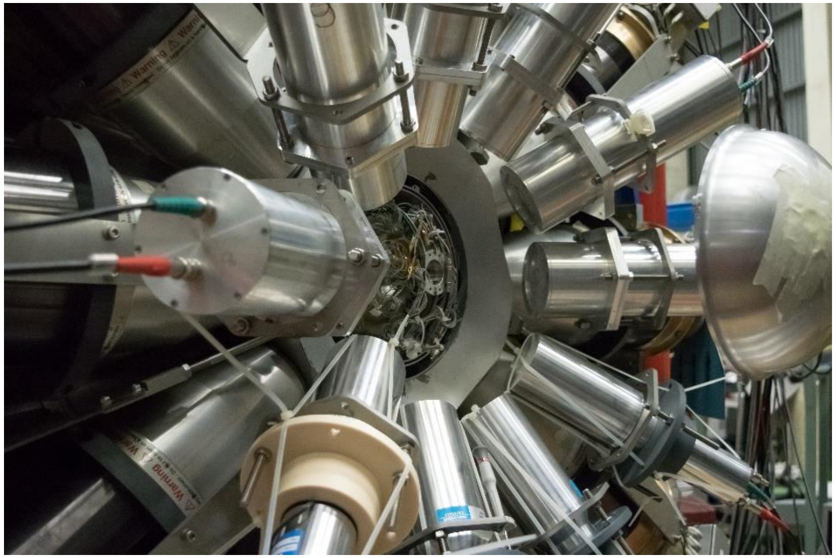
Evidence of mass dependence of α^2

E. Farnea et al. Phys. Lett. B 551 (2002)

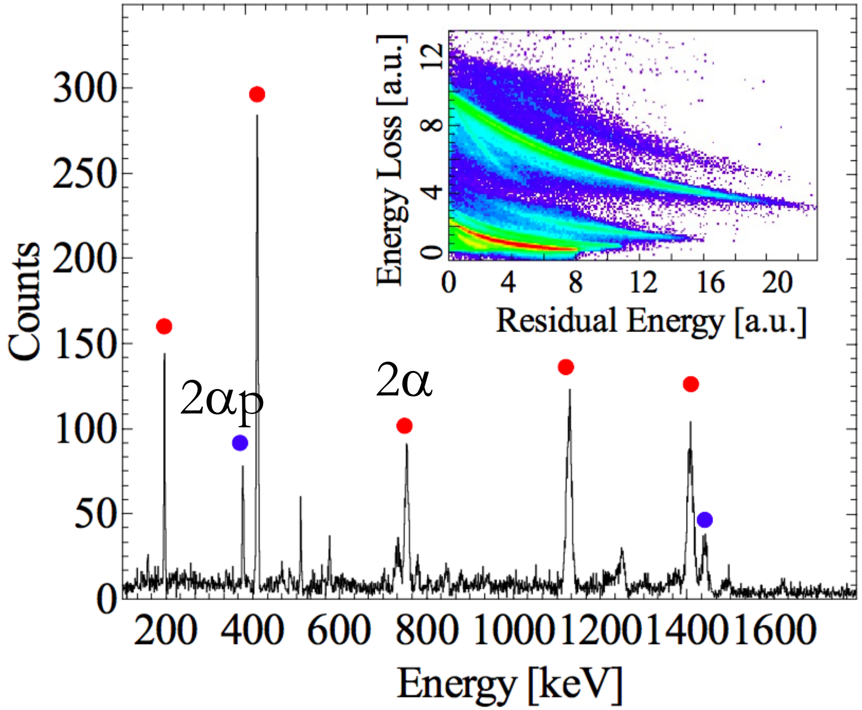
Experimental technique

GALILEO @ LNL

GALILEO
LaBr3:Ce detectors
EUCLIDES
NeutronWall

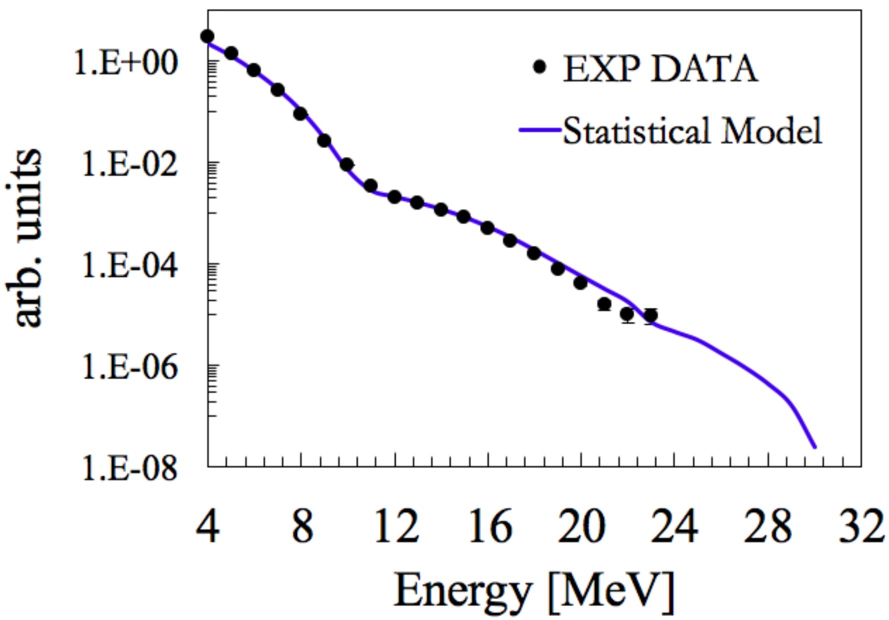


ISOSPIN MIXING IN 60Zn



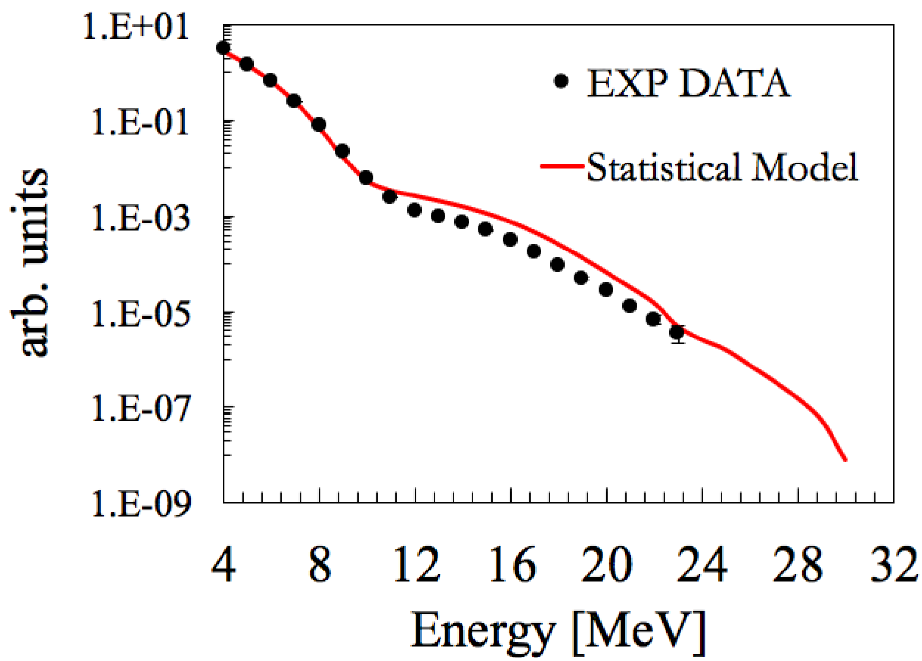
Experimental technique

$^{32}S + ^{30}Si \rightarrow ^{62}Zn$ @ 75 MeV



Data are reproduced by using a **standard statistical model**

$^{32}S + ^{28}Si \rightarrow ^{60}Zn$ @ 86 MeV



- GDR strength clearly **inhibited**
- Evidence of **E1 selection rule**
- How much??→ **Isospin Mixing**

Beyond nuclear structure: CKM matrix

PHYSICAL REVIEW C **82**, 065501 (2010)

Comparative tests of isospin-symmetry-breaking corrections to superallowed $0^+ \rightarrow 0^+$ nuclear β decay

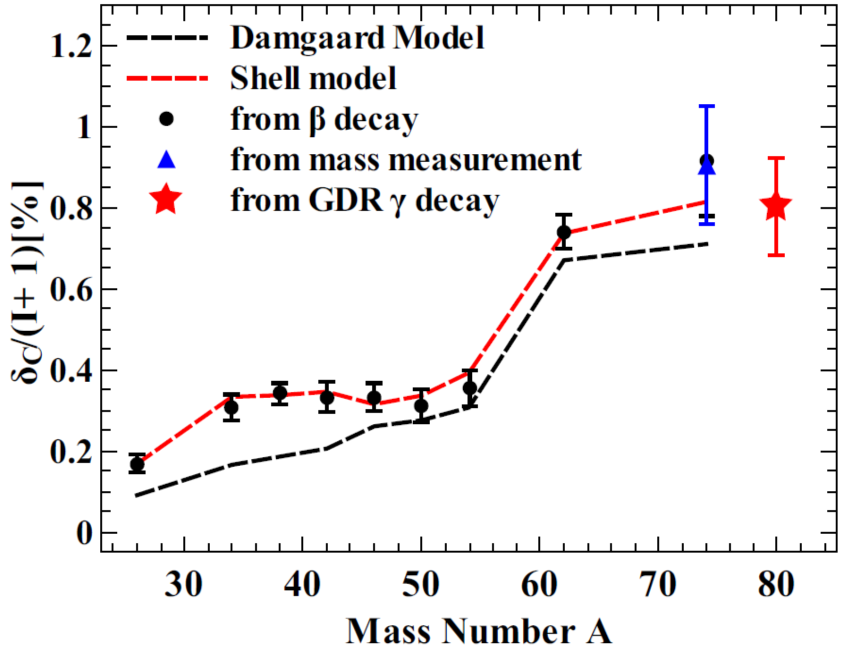
I. S. Towner[*] and J. C. Hardy[†]

$$\mathcal{F}t \equiv ft(1+\delta'_R)(1+\delta_{NS}-\delta_C)$$

Auerbach (***PRC 79 035502 (2009)***) mixing between I=0 and I=1 in the parent nucleus

$$\delta_C = 4(I+1)\frac{V_1}{41\xi A^{2/3}}\alpha^2$$

Isospin mixing



I.S. Towner and J.C. Hardy PRC 82, 065501 (2010)

Summary

- Giant Resonances are important tools to investigate fundamental nuclear properties
- The isospin is a fundamental ingredient for nuclear structure and nuclear reaction
- The isospin symmetry is broken in nuclei
- Importance beyond nuclear field
- GDR can be a good probe to observe the isospin symmetry breaking

Collaboration

S. Ceruti[1], A. Mentana[1], G. Gosta[1] M. Ciemala[2], F. Camera[1], A. Bracco[1], G. Benzoni[1], N. Blasi[1], G. Bocchi[1], S. Brambilla[1], F.C.L. Crespi[1], A. Giaz[1], S. Leoni[1], B. Million[1], O. Wieland[1], M. Kmiecik[2], A. Maj[2], B. Wasilewska[2], M. Zieblinski[2], D. Filipescu[3], D. Ghita[3], V. Zamfir[3], J.J. Valiente-Dobon[4], G. de Angelis[4], F. Galtarossa[4], A. Goasduff[4], G. Jaworski[4], D.R. Napoli[4], D. Testov[4], M. Siciliano[4], T. Marchi[4], D. Mengoni[5], D. Bazzacco[5], A. Boso[5], P.R. John[5], F. Recchia[5], R. Raabe[6], O. Poleshchuk[6], J. Yang[6].

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[2] *Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland.*
[3] *Extreme Light Infrastructure - Nuclear Physics (ELI-NP)\ Horia Hulubei National Institute for R&D in Physics and Nuclear Engineering (IFIN-HH), Bucharest-Magurele, Romania*
[4] *INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy.*
[5] *INFN, Sez. di Padova, Padova, Italy. and Dip. di Fisica dell'Università di Padova, Padova, Italy.*
[6] *KU Leuven, Department of Physics and Astronomy Instituut voor Kern- en Stralingsfysica Celestijnenlaan 100D 3001 Leuven, Belgium*

Thank you
for your
attention

Experimental technique

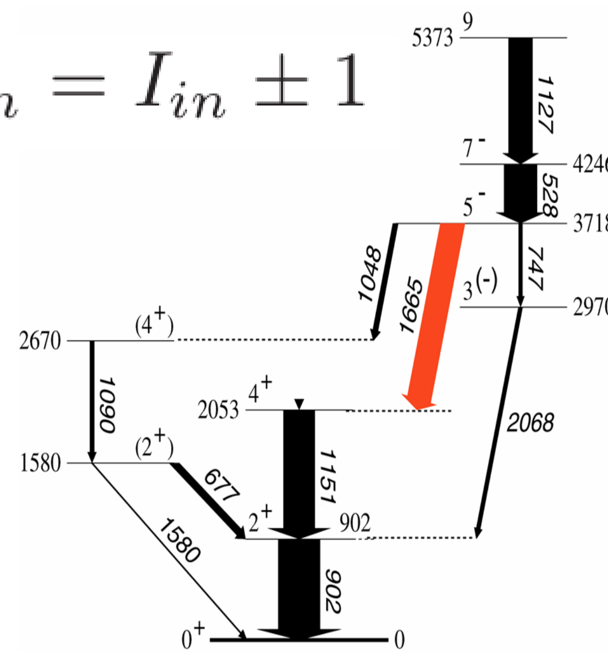
- In N=Z nuclei I = 0
- **Electric Dipole transitions (E1)** has an isovector nature

Selection rule:
E1 decays
correspond to
change of isospin

$$I_{fin} = I_{in} \pm 1$$

The **mixing** increases the γ decay yield

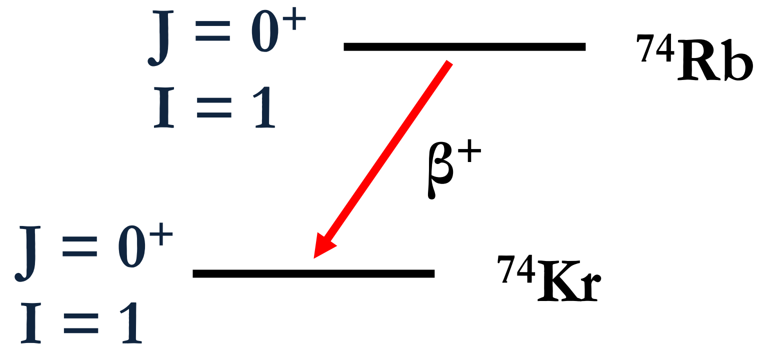
The observed **E1 strength** is a signature of the mixing



E. Farnea et al. Phys. Lett. (2002)

α^2=2.50(+1.0-0.7)%

Beyond nuclear structure: CKM matrix



$$0^{+} \rightarrow 0^{+}, \Delta I = 0$$

Superallowed Fermi beta transitions

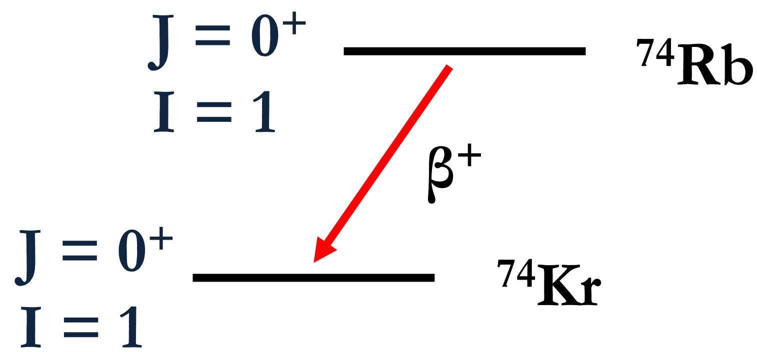
↓

ft depends only on universal quantity.
It **<u>should</u>** be indiependent on the nuclear mass.

Universality of the vector coupling constant Gv

$$ft = \frac{K}{|M_F|^2 G_V^2} = \frac{K}{|M_F|^2 G_F^2 V_{ud}^2}$$

Beyond nuclear structure: CKM matrix



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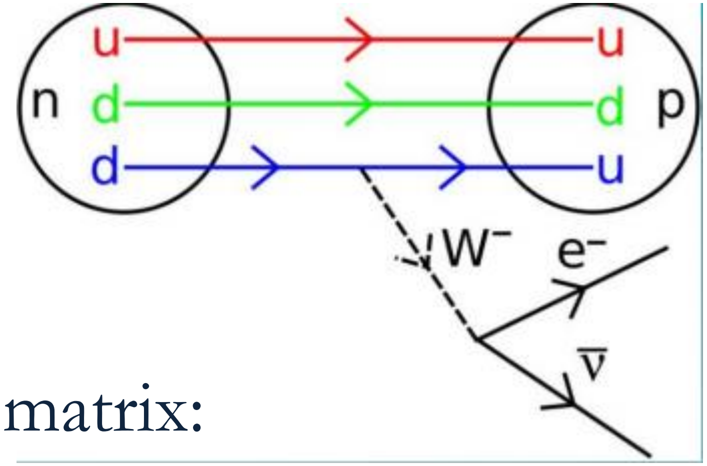
Measuring ft values in several nuclei one can extract <ft>
→ <Gv> & <Vud> & unitarity of CKM

Beyond nuclear structure: CKM matrix

Cabibbo–Kobayashi–Maskawa matrix (**CKM** Matrix) contains information on the strength of weak decay between different quarks.

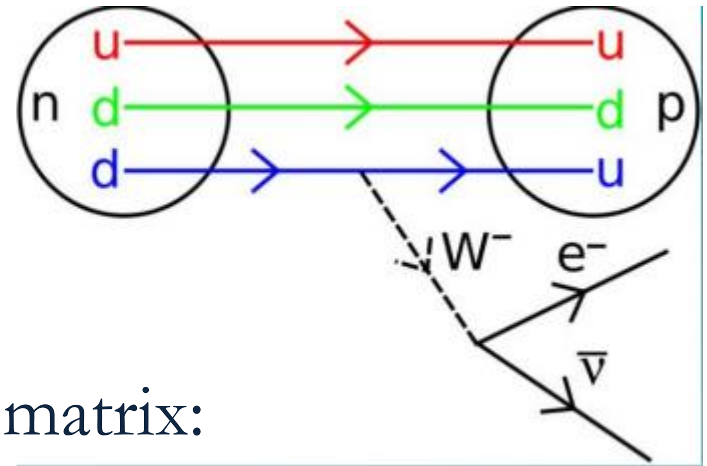


Standard Model **CKM** is a unitary matrix:

V_{ud}

$$\mathbf{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Cabibbo–Kobayashi–Maskawa matrix (**CKM** Matrix) contains information on the strength of weak decay between different quarks.



Standard Model **CKM** is a unitary matrix:

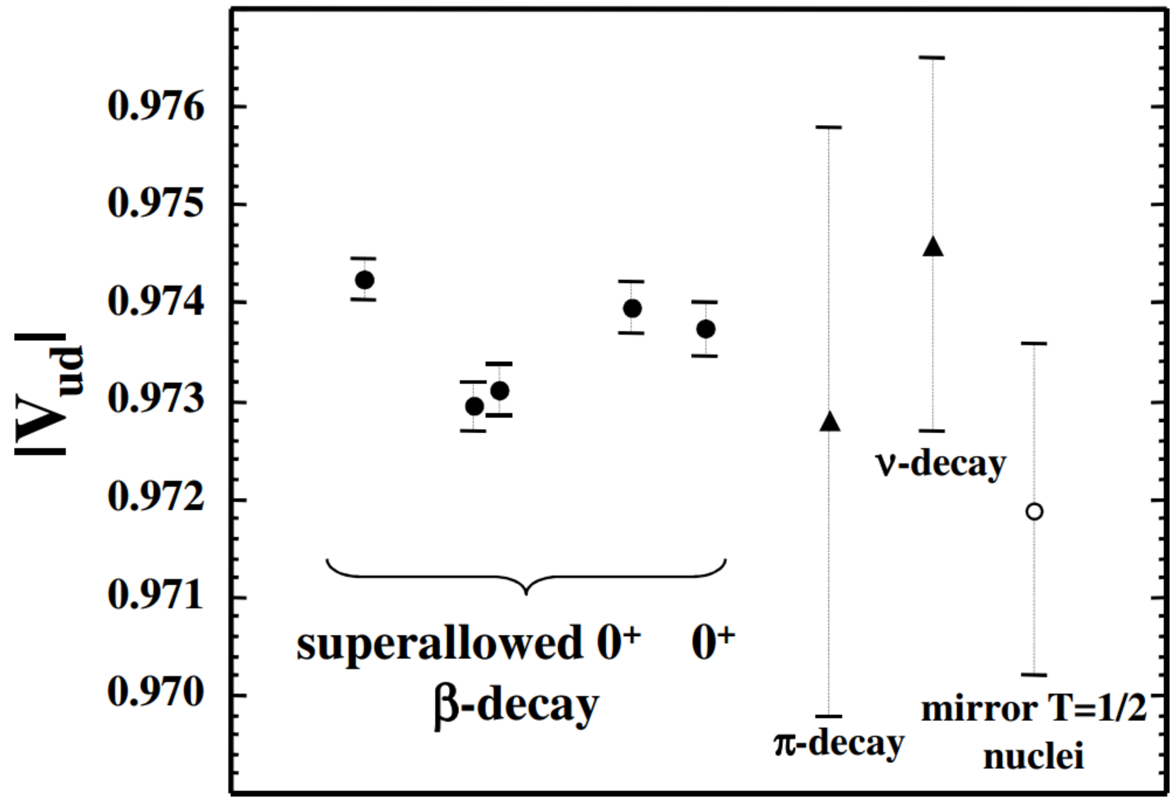
V_{ud}

$$V_{\mathrm{CKM}} = \begin{pmatrix} 0.97434^{+0.00011}_{-0.00012} & 0.22506 \pm 0.00050 & 0.00357 \pm 0.00015 \\ 0.22492 \pm 0.00050 & 0.97351 \pm 0.00013 & 0.0411 \pm 0.0013 \\ 0.00875^{+0.00032}_{-0.00033} & 0.0403 \pm 0.0013 & 0.99915 \pm 0.00005 \end{pmatrix}$$

$$0 \quad 0 \quad 1$$

C. Amsler et. al. [Particle Data Group], Phys. Lett. B 667 (2008)

Beyond nuclear structure: CKM matrix

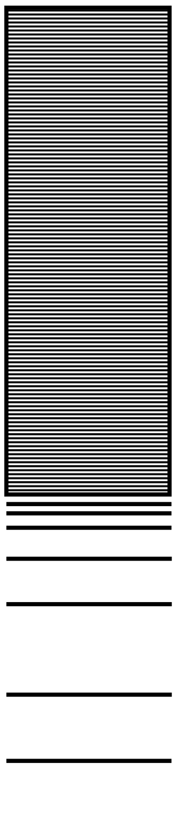


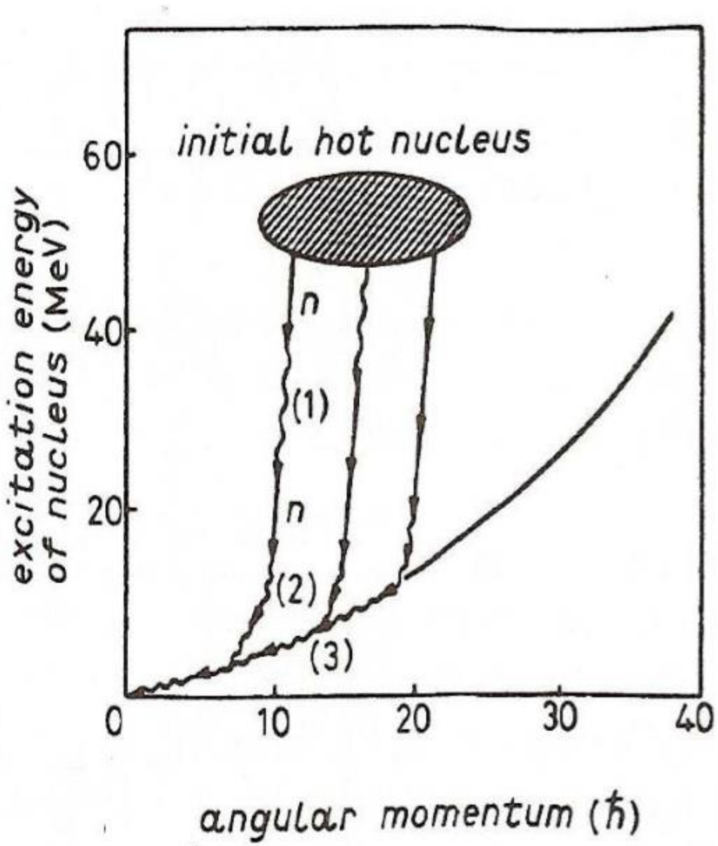
- CKM unitarity 0.05%

W. Satula et al. PRL 106, 132502 (2011)

Isospin symmetry breaking

CN





Decay described by using a statistical approach

$$\Gamma_i(E^*, J_{CN}) = \frac{1}{2\pi\rho_{CN}(E^*, J_{CN})}\int d\epsilon \sum_{J_d=0}^{\infty} \sum_{|J_{CN}-J_d|}^{J_{CN}+J_d} \sum_{l=|J-S_l|}^{J+S_l} T_l(\epsilon)\rho_d(E^* - B_i - \epsilon)$$

F. Pühlhofer, Nucl. Phys. A 280, 267 (1977)

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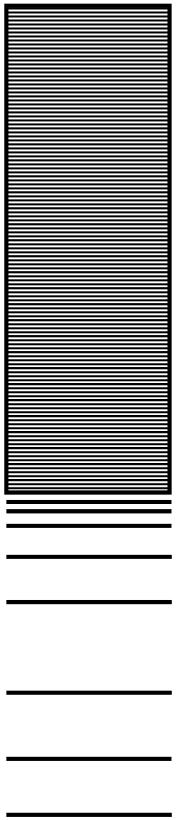
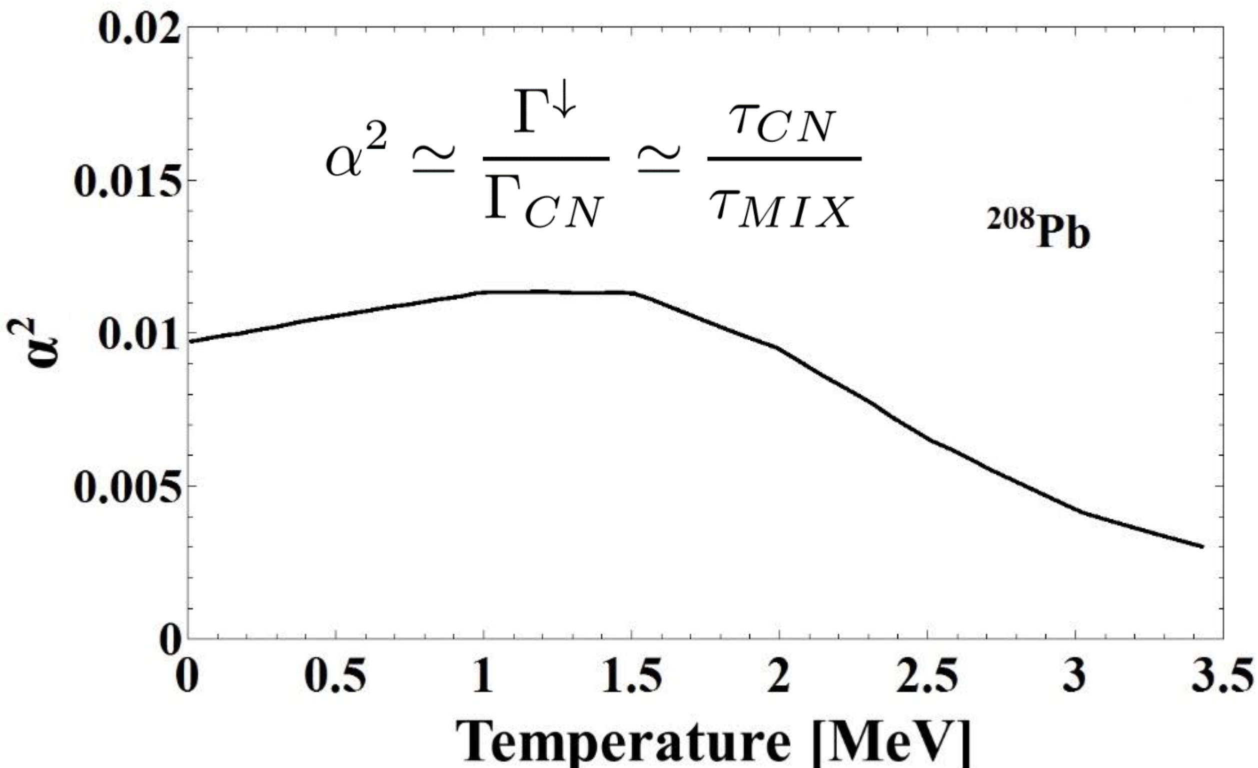


- At high excitation energy the number of levels is very high. A=100 E*=50 MeV→ **10^{17} states/MeV**
- The nucleus has a **finite lifetime**
- **Mixing governed by the competition with the CN decay**
- The nucleus can decay **before** the mixing effects
- At high excitation energy (and thus at short lifetime) the isospin symmetry is **restored**

H. Morinaga, Phys. Rev. 97, 444 (1955)

Isospin symmetry breaking

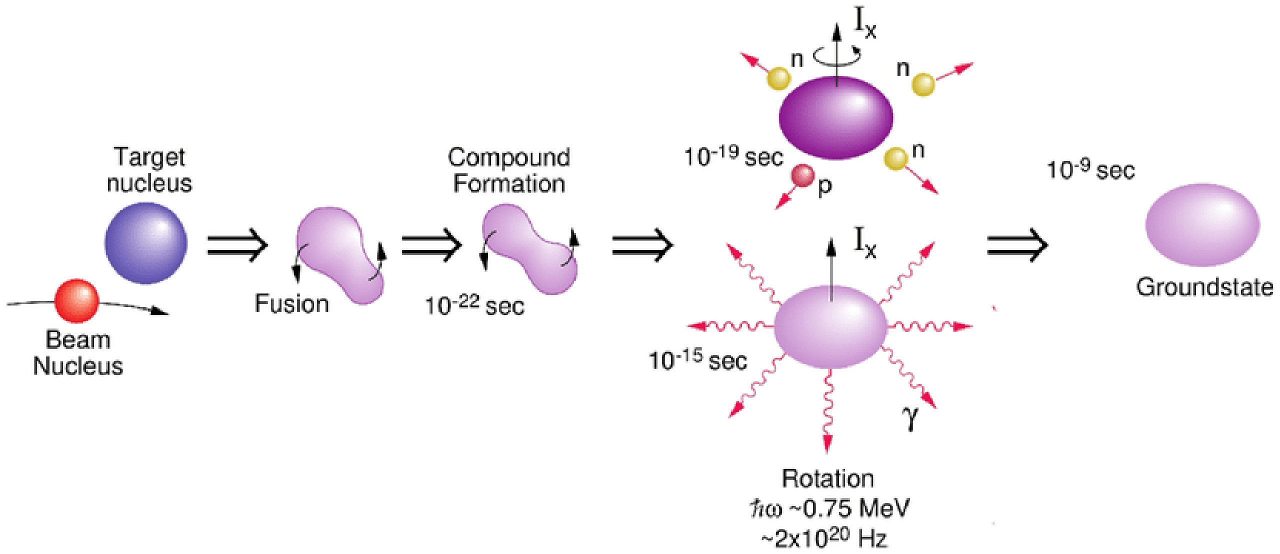


- Competition between the decay and the mixing process
- At high **E***(or **T**) a better symmetry is expected
- **dynamical behavior**

G. Colo et al ., PRC 54 (1996) H. Sagawa et al PLB 444 1998. 1–6

Experimental technique

Symmetric fusion reaction to form I = 0 compound nucleus



The isospin is a conserved quantity in nuclear reaction!